7

Observations: Extreme Weather

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Key Findings

The following points summarize the main findings of this chapter:

- Air temperature variability decreases as mean air temperature rises, on all time scales.

- Therefore the claim that global warming will lead to more extremes of climate and weather, including of temperature itself, seems theoretically unsound; the claim is also unsupported by empirical evidence.

- Although specific regions have experienced significant changes in the intensity or number of extreme events over the twentieth century, for the globe as a whole no relationship exists between such events and global warming over the past 100 years.

- Observations from across the planet demonstrate droughts have not become more extreme or erratic in response to global warming. In most cases, the worst droughts in recorded meteorological history were much milder than droughts that occurred periodically during much colder times.

- There is little or no evidence that precipitation will become more variable and intense in a warming world; indeed, some observations show just the opposite.

- There has been no significant increase in either the frequency or intensity of stormy weather in the modern era.

- Despite the supposedly "unprecedented" warming of the twentieth century, there has been no increase in the intensity or frequency of tropical cyclones globally or in any of the specific ocean basins.

Introduction

For more than two decades the United Nations Intergovernmental Panel on Climate Change (IPCC) has supported the model-based narrative that carbon dioxide (CO_2)-induced global warming will cause (or is already causing) extreme weather, including more frequent and more severe heat waves, precipitation extremes (droughts and floods), storms, tropical cyclones, and other extreme weather-related events. With respect to observed changes in extreme weather, the 2012 IPCC special report on extreme weather (Field *et al*., 2012) states:

> There is evidence from observations gathered since 1950 of change in some extremes. Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning 'low confidence' in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme.

With respect to projected changes in extreme weather, that special report states:

> Confidence in projecting changes in the direction and magnitude of climate extremes depends on many factors, including the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models. … Assigning 'low confidence' for projections of a specific extreme neither implies nor excludes the possibility of changes in this extreme.

Chapter 1 of this NIPCC report presents evidence the climate models are fraught with numerous biases and shortcomings that lead to significant errors in their projections, leaving model projections highly questionable at best. Such a conclusion is especially true for projections of extreme weather events, which are much more difficult to model than average conditions and operate on much larger spatial and temporal scales. Because the models were critically examined in Chapter 1, the evaluation of their extreme weather projections will be of minor focus here. Instead, the majority of material presented in this chapter focuses on empirical observations.

More specifically, this chapter reviews historical trends in extreme weather events and examines how they interrelate with other weather and climate variables. It is clear in almost every instance of each extreme weather event examined, there is little support for predictions that CO_2-induced global warming will increase either the frequency or intensity of those events. The real-world data overwhelmingly support an opposite conclusion: Weather will more likely be less extreme in a warmer world.

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7.1 Temperature

One of the projected negative consequences of global warming is an increase in climatic variability, including more frequent extreme temperatures (mainly at the warm end of the temperature spectrum). The IPCC's *Fifth Assessment Report* claims more evidence now exists that "the AR4 conclusion that surface temperature extremes have likely been affected by anthropogenic forcing" is correct, adding "we now conclude that it is very likely that anthropogenic forcing has contributed to the observed changes in temperature extremes since the mid-20th century" (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, model projections suggest these extreme events will increase throughout this century as a consequence of CO_2-induced global warming.

It is a relatively easy matter to either substantiate or refute such claims by examining trends of extreme temperatures over the past century or so. If global warming truly has been occurring at an unprecedented rate over the past hundred years and global warming causes an increase in extreme weather events, as often claimed, temperature variability and extreme temperature events should be increasing. In the subsections of Section 7.1 that follow, we investigate this topic as it pertains to locations in Asia (7.1.1), Europe (7.1.2), North America (7.1.3), and Other Areas across the globe (7.1.4). Specifically, we present the findings of many peer-reviewed papers that do not support the IPCC claims in regard to temperature extremes.

Contrary to model projections, the studies referenced in this section indicate a warmer climate does not produce a more variable climate. The data presented herein suggest a warmer climate may very well be less variable and less extreme, if any change occurs at all. Projections of more frequent and more intense temperature extremes do not appear to be supported by the majority of scientific observations as reported in the peer-reviewed literature.

7.1.1 Asia

This subsection highlights several peer-reviewed studies from Asia that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Yadav *et al.* (2004) obtained a long tree-ring series from widely spaced Himalayan cedar trees in an effort to develop a temperature history of the western Himalayas for the period AD 1226–2000. "Since the 16th century," they write, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226–1500), reflecting unstable climate during the Little Ice Age (LIA)." They note juniper tree-ring chronologies from central Tibet provide similar results (Braeuning, 2001) and "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." In a study of the winter half-year temperatures of a large part of China, Ge *et al.* (2003) identified greater temperature anomalies during the 1600s than in the 1980s and 1990s. Zhang and Gaston (2004) report an even greater extreme anomaly occurred in China in the summer of 1743.

This eighteenth century "heat wave attack" was felt throughout northern China, including Beijing, Tianjin, and the provinces of Hebei, Xhanxi, and Shandong. One report from Tianjin at the time said "July's heat is insupportable; fields full of cracks; rocks scorched; melting metal on mast top; many died of heat." In Gaoyi the temperature was said to be "as hot as fire in rooms and under heavy shades of trees, with melting lead and tin at midday and many died of thirst on 19–26 July." Shenze, Changzhi, Fushan, Gaoqing, and Pingyuan reported people dying from the intense heat, with the communication from Shenze saying "the disaster is indeed unprecedented." Officials reported 11,400 people died from the heat in Beijing and its suburbs between July 14 and July 25. That was a vast underestimate of the real death toll, for it included only "poor people, like craftsmen, or workers," neglecting the deaths of "the well-off and the ones in service," of which "there were a large number." And that was the death toll in the Beijing area alone.

Just how unusual was this deadly heat wave? According to Zhang and Gaston (2004), it was the hottest period of the hottest summer experienced in north China during the past seven centuries, where peak warmth exceeded the modern-day extreme heat wave high temperature by 2°C. It occurred in 1743, sandwiched between two of the coldest intervals of the Little Ice Age, as opposed to occurring during the modern era with its more-precise instruments for measuring temperature and other weather elements.

Focusing in on the modern era, Zhai and Pan (2003) derived trends in the frequencies of warm days and nights, cool days and nights, and hot days and frost days for the whole of China over the period 1951–1999, based on daily surface air temperature data obtained from approximately 200 weather observation stations scattered throughout the country.

Over the period of study, and especially throughout the 1980s and 1990s, the authors found increases in the numbers of warm days and nights, and there were decreases in the numbers of cool days and nights, consistent with an overall increase in mean daily temperature. Nevertheless, at the extreme hot end of the temperature spectrum, the authors report "the number of days with daily maximum temperature above 35°C showed a slightly decreasing trend for China as a whole." At the extreme cold end of the spectrum, the number of frost days with daily minimum temperature below 0°C declined at the rate of 2.4 days per decade. The data from approximately 200 locations across China reveal during the second half of the twentieth century there was a reduction in extreme cold weather events without any concomitant increase in extreme hot weather.

Zhou and Ren (2011) evaluated trends in 15 extreme temperature indices for the period 1961–2008 using daily temperature records from 526 measurement stations included among the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration. Based on the earlier findings of Zhou and Ren (2009)—which indicated the contribution of urban warming to overall warming often exceeded 50%—they adjusted their results to account for the impact of each site's urban heat island effect.

Zhou and Ren discovered "urbanization intensified the downward trend in cold index series and the upward trend in warm indices related to minimum temperature." They report "the urbanization effect on the series of extreme temperature indices was statistically significant for the downward trends in frost days, daily temperature range, cool nights, and cool days," as well as for "the upward trends in summer days, tropical nights, daily maximum temperature, daily minimum temperature, and warm nights." For these indices, they state "the contributions of the urbanization effect to the overall trends ranged from 10 to 100%, with the largest contributions coming from tropical nights, daily temperature range, daily maximum temperature and daily minimum temperature," adding "the decrease in daily temperature range at the national stations in North China was caused entirely by urbanization." The two researchers concluded, "more attention needs to be given to the issue [of urbanization on temperature] in future studies," something IPCC contributors and reviewers need to look at much more closely in the future than they have in the past. The urban influence can explain up to 100% of the change in extreme temperatures over the past half-century in many locations, leaving little or no room for any other influence, including CO_2-induced global warming.

Deng *et al*. (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 obtained from 10 meteorological stations to determine the number of hot days (HDs, at or above 35°C), very hot days (VHDs, at or above 38°C), and extremely hot days (EHDs, at or above 40°C) in an effort to address temperature extremes within the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. They defined a heat wave (HW) as a period with no fewer than three consecutive HDs, a short heat wave (SHW) as being at least six days long, and a long heat wave (LHW) as a heat wave exceeding six days.

Between 1958 and 2007, the three Chinese researchers reported, their study area experienced a mean annual warming trend, but with slight decreasing trends in spring and summer temperatures. Extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that "the frequencies of HWs and LHWs in the recent years were no larger than the late 1950s and early 1960s." They indicated "coupled with the extreme low frequency in the 1980s, HWs and LHWs showed a slight linear decreasing trend in the past 50 years." They found the most recent frequency of heat waves "does not outnumber 1959 or 1961," and "none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003."

Deng *et al*. conclude, "compared with the 1950s and 1960s, SHWs instead of LHWs have taken place more often," which, as they describe it, "is desirable, as longer duration leads to higher mortality," citing Tan *et al*. (2007). For the Three Gorges area of China, even a mean annual warming trend over the past half-century has not led to an increase in the frequency of extremely long heat waves.

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7.1.2 Europe

This subsection highlights several peer-reviewed studies from Europe that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Beginning with a historic view of the topic, the study of Jones and Briffa (2006), in their words, focused "on one of the most interesting times of the early instrumental period in northwest Europe (from 1730–1745), attempting to place the extremely cold year of 1740 and the unusual warmth of the 1730s decade in a longer context." The authors relied primarily on "long (and independent) instrumental records together with extensive documentary evidence," as well as "unpublished subjective circulation charts developed by the late Hubert Lamb" and "others recently developed using more objective modern reconstruction techniques."

According to the two researchers from the Climatic Research Unit of the University of East Anglia, the analysis revealed "the period 1740–1743 has been shown to be the driest period of the last 280 years, with the year 1740 the coldest recorded over the British Isles since comparable records began in 1659." They note the record cold of 1740 "is all the more remarkable given the anomalous warmth of the 1730s," which was "the warmest in three of the long temperatures series (Central England Temperature, De Bilt and Uppsala) until the 1990s occurred."

In discussing their findings, Jones and Briffa state their study "highlights how estimates of natural climatic variability in this region based on more recent data may not fully encompass the possible known range" and "consideration of variability in these records from the early 19th century, therefore, may underestimate the range that is possible." The instrumental record is simply not long enough to provide a true picture of natural temperature variability in terms of what is possible in the absence of the influence of anthropogenic greenhouse gases.

Manrique and Fernandez-Cancio (2000) employed a network of approximately 1,000 samples of tree-ring series representative of a significant part of Spain to reconstruct thousand-year chronologies of temperature and precipitation. They used the database to identify anomalies in these parameters that varied from their means by more than four standard deviations. They found the greatest concentration of extreme climatic excursions, which they describe as "the outstanding oscillations of the Little Ice Age," occurred between AD 1400 and 1600, during a period when extreme low temperatures reached their maximum frequency.

Focusing on the past century, Rebetez (2001) analyzed day-to-day variability in two temperature series from Switzerland over the period 1901–1999, during which the two sites experienced temperature increases of 1.2 and 1.5°C. Their work revealed warmer temperatures led to a reduction in temperature variability at both locations. They found "warmer temperatures are accompanied by a general reduction of variability, both in daily temperature range and in the monthly day-to-day variability," indicating even on a much finer time scale, cooling rather than warming brings an increase in temperature variability.

Beniston and Goyette (2007) noted "it has been assumed in numerous investigations related to climatic change that a warmer climate may also be a more variable climate (e.g., Katz and Brown, 1992; IPCC, 2001; Schar *et al*., 2004)" and "such statements are often supported by climate models results, as for example in the analysis of GCM and/or RCM simulated temperature and precipitation (Mearns *et al*., 1995; Mearns *et al*., 1990)." Therefore, they observed, "it is of interest to investigate whether, based on long time-series of observational data, this hypothesis is indeed verified in a climate that has experienced a warming of 2°C or more."

Noting twentieth-century warming in the alpine area of Europe "is 2–3 times greater than the global average (Jungo and Beniston, 2001) and provides an observational framework that makes it possible to address the issue of links between mean temperature and its variance," Beniston and Goyette focused their analysis on one Swiss site representative of low elevation (Basel, 369 m above sea level) and another Swiss site representative of high elevation (Saentis, 2500 m above sea level), both of which "have proven their quality in a number of previous studies (Jungo and Beniston, 2001; Beniston and Jungo, 2002; Beniston and Stephenson, 2004; Beniston and Diaz, 2004)," where they say it was determined conclusions based on data from these sites "also apply to most of the other Swiss sites."

Beniston and Goyette reported observational data since 1900 at both the low- and high-elevation sites indicate "the inter-annual and decadal variability of both maximum and minimum daily temperatures has in fact *decreased* [emphasis in the original] over the course of the 20th century despite the strong warming that has been observed in the intervening period." These findings, they added, "are consistent with the temperature analysis carried out by Michaels *et al*. (1998), where their results also do not support the hypothesis that temperatures have become more variable as global temperatures have increased during the 20th century." In addition, they found "the principal reason for this reduction in variability is related to the strong increase in the persistence of certain weather patterns at the expense of other types." Thus, the Swiss researchers reported their observations show "contrary to what is commonly hypothesized, climate variability does not necessarily increase as climate warms." They emphasized "the variance of temperature has actually decreased in Switzerland since the 1960s and 1970s at a time when mean temperatures have risen considerably."

Chase *et al*. (2006) noted much was made of the supposed uniqueness of the summer of 2003 European heat wave, its implied connection to CO_2-induced global warming, and the proposal that it was evidence of a climatic regime shift to one of greater variability that supports the more frequent occurrence of more extreme warm events (Schar *et al*., 2004; Stott *et al*., 2004; Trigo *et al*., 2005). The group of four researchers utilized NCEP global reanalysis data for the period 1979–2003 to calculate extreme tropospheric temperature events over the region 22°N to 80°N throughout the June-July-August period (and globally using annual averages), after which they compared the results with the corresponding particulars of the European heat wave of 2003 in terms of "standard deviations exceeded and correlations between regional extremes and temperatures at larger spatial scales."

Their analysis revealed "extreme warm anomalies equally, or more, unusual than the 2003 heat wave occur regularly," "extreme cold anomalies also occur regularly and can exceed the magnitude of the 2003 warm anomaly," "warmer than average years have more regional heat waves and colder than average years have more cold waves," "natural variability in the form of El Niño and volcanism appears of much greater importance than any general warming trend in causing extreme regional temperature anomalies," and "regression analyses do not provide strong support for the idea that regional heat or cold waves are significantly increasing or decreasing with time during the period considered here."

Chase *et al*. conclude their analysis "does not support the contention that similar anomalies as seen in summer 2003 are unlikely to recur without invoking a non-stationary statistical regime with a higher average temperature and increased variability." In other words, the 2003 European summer heat wave implies nothing at all about CO_2-induced global warming. It was merely a rare, but not unprecedented, weather event, of which there have been several other examples (both hot and cold, and some stronger) over the past quarter-century.

In another study conducted in an effort to understand the significance of a modern heat wave from an historical perspective, Dole *et al*. (2011) observed "the 2010 summer heat wave in western Russia was extraordinary, with the region experiencing the warmest July since at least 1880 and numerous locations setting all-time maximum temperature records." They noted "questions of vital societal interest are whether the 2010 Russian heat wave might have been anticipated, and to what extent human-caused greenhouse gas emissions played a role."

Dole *et al*. used climate model simulations and observational data "to determine the impact of observed sea surface temperatures, sea ice conditions and greenhouse gas concentrations." The nine U.S. researchers found "analysis of forced model simulations indicates that neither human influences nor other slowly evolving ocean boundary conditions contributed substantially to the magnitude of the heat wave." They observed the model simulations provided "evidence that such an intense event could be produced through natural variability alone." Similarly, they stated "July surface temperatures for the region impacted by the 2010 Russian heat wave show no significant warming trend over the prior 130-year period from 1880–2009." They noted "a linear trend calculation yields a total temperature change over the 130 years of -0.1°C." In addition, they observed "no significant difference exists between July temperatures over western Russia averaged for the last 65 years (1945–2009) versus the prior 65 years (1880–1944)" and "there is also no clear indication of a trend toward increasing warm extremes." Finally, although there was a slightly higher variability in temperature in the latter period, the increase was "not statistically significant."

"In summary," Dole *et al*. observed, "the analysis of the observed 1880–2009 time series shows that no statistically significant long-term change is detected in either the mean or variability of western Russia July temperatures, implying that for this region an anthropogenic climate change signal has yet to emerge above the natural background variability." They concluded their analysis "points to a primarily natural cause for the Russian heat wave," noting the event "appears to be mainly due to internal atmospheric dynamical processes that produced and maintained an intense and long-lived blocking event." There were no indications "blocking would increase in response to increasing greenhouse gases," the authors reported.

In a study designed to assess the extent to which temperature variability may have increased in Austria since the late nineteenth century, Hiebl and Hofstatter (2012) took a systematic and objective approach to the issue of air temperature on a local scale, based on 140 years of data from Vienna-Hohe Warte, Kremsmunster, Innsbruck-University, Sonnblick, and Graz-University.

Starting from a low level of temperature variability around 1900, the two Austrian researchers reported a slow and steady rise in variability during the twentieth century. They also reported a "period of persistently high variability levels before 1900," which led them to conclude the "relatively high levels of temperature variability during the most recent warm decades from 1990 to 2010 are put into perspective by similar variability levels during the cold late 19th century." They added, "when compared to its inter-annual fluctuations and the evolution of temperature itself, high-frequency temperature variability in the course of the recent 117–139 years appears to be a stable climate feature." Hiebl and Hofstatter concluded concerns about "an increasing number and strength of temperature extremes in terms of deviations from the mean state in the past decades cannot be maintained" and "exaggerated statements seem irresponsible."

Bohm (2012) observed "South Central Europe is among the spatially densest regions in terms of early instrumental climate data," citing Auer *et al*. (2007). He explained this fact allows for successfully testing for homogeneity and developing "a larger number of very long instrumental climate time series at monthly resolution than elsewhere," noting the resulting long time series subset of the greater alpine region provides a great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the "anthropogenic climate" of the past three decades. More specifically, he reported "the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year 'normal periods' from 1771–1800 to 1981–2010."

Bohm found "the overwhelming majority of seasonal and annual sub-regional variability trends is not significant." In the case of precipitation, for example, he observed, "there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period." Regarding temperature, he reported "most of the variability trends are insignificantly decreasing." In a "special analysis" of the recent 1981–2010 period that may be considered the first "normal period" under dominant greenhouse-gas-forcing, he found all extremes "remaining well within the range of the preceding ones under mainly natural forcing," and "in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable."

Bohm concludes "the … evidence [is clear] that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period."

Jeong *et al*. (2010) began by recognizing the model-based IPCC *Fourth Assessment Report* claim suggesting future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming, citing the work of Meehl and Tebaldi (2004) and Della-Marta *et al*. (2007). In a model-based assessment of this hypothesis, Jeong *et al*. investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments," where land surface processes are calculated by the Community Land Model (version 3) described by Oleson *et al*. (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables. The six scientists reported their calculations indicate "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included," and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." In addition, they found "the greening also tends to reduce the frequency and duration of heat waves."

Jeong *et al*. indicated just how easily the incorporation of a new suite of knowledge, in even the best climate models of the day, can dramatically alter what the IPCC and others purport to be reality, including what they say about the frequency and duration of heat waves. Yet in conjunction with their model-based work, real-world data from the past revealed extreme temperatures tend to be less frequent and less severe during warmer climatic periods than during colder ones.

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7.1.3 North America

This subsection highlights several peer-reviewed studies from North America that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Shabbar and Bonsal (2003) examined trends and variability in the frequency, duration, and intensity of winter cold and warm spells in Canada during the second half of the twentieth century. For the period 1950–1998, they found western Canada experienced decreases in the frequency, duration, and intensity of winter cold spells. In the east, however, distinct increases in the frequency and duration of winter cold spells occurred. With respect to winter warm spells, significant increases in both their frequency and duration were observed across most of Canada, with the exception of the extreme northeastern part of the country, where warm spells appear to be becoming shorter and less frequent. In the mean, therefore, there appear to be close-to-compensating trends in the frequency and intensity of winter cold spells in different parts of Canada, while winter warm spells appear to be increasing somewhat.

Khaliq *et al.* (2007) noted "extreme climate events are receiving increased attention because of the possibility of increases in their frequency and severity in future climate as a result of enhanced concentrations of greenhouse gases in the atmosphere and associated atmospheric warming" and "transient climate change simulations performed with both Global Climate Models and Regional Climate Models suggest increased frequencies of extreme high temperature events." The five researchers assessed temporal changes in the frequency of occurrence and durations of heat waves based on data acquired at seven weather stations located in southern Quebec for the 60-year period 1941–2000. For heat spells defined in terms of daily maximum air temperature, the majority of extreme events showed "a negative time-trend with statistically significant decreases (at 10% level)," while almost all of the heat spells defined in terms of daily minimum air temperature showed "a positive time-trend with many strong increases (i.e., statistically significant at 5% level) at all of the stations." Khaliq *et al.* stated "a possible interpretation of the observed trends is that the maximum temperature values are getting less hot and minimum temperature values are getting less cold with time," signaling a reduction in overall temperature variability.

Bonsal *et al.* (2001) reported similar findings several years earlier, analyzing spatial and temporal characteristics of daily and extreme temperature-related variables across Canada over the period 1900–1998. They found "significant trends toward fewer days with extreme low temperature during winter, spring, and summer" as well as "trends toward more days with extreme high temperature in winter and spring," but noted "these are not as pronounced as the decreases to extreme low values." They found "no indication of any consistent changes to the magnitude of extreme high daily maximum temperature during summer" and "in general, day-to-day temperature variability has decreased over most of southern Canada during the twentieth century," evidenced by a greater increase in daily minimum (as opposed to maximum) extreme temperature values.

Taking a much longer view of the subject, Fallu *et al*. (2005) derived a 6,700-year temperature history for northern Quebec, Canada. They found after an initial increase in temperature that lasted from 6400 to 4900 cal. yr BP, a warm phase occurred from 4900 to ca. 1500 cal. yr BP. They reported the data obtained from this latter portion of the sediment core "suggest the most stable paleoclimatic conditions during this period." Then came what they call the "recent cooling," which lasted from ca. 1500 cal. yr BP to modern times, during which interval, they found, "lake water temperature apparently became increasingly unstable." Accordingly, temperature variability in this region declined when the climate warmed.

Kunkel *et al*. (1999) investigated the occurrence of intense heat and cold waves from 876 locations in the southwestern United States over the period 1931–1997. They found a decline in exceedance probability threshold since 1930 for heat waves, and no trend was identified for cold spells (see Figures 7.1.3.1 and 7.1.3.2). As a result of these and other findings, Kunkel *et al*. concluded there has been "no evidence of changes in the frequency of intense heat or cold waves."

Iskenderian and Rosen (2000) studied two mid-tropospheric temperature datasets spanning the past 40 years, calculating day-to-day variability within each month, season, and year. Averaged over the entire Northern Hemisphere, they found mid-tropospheric temperature variability exhibited a slight upward trend since the late 1950s in one of the datasets, but "this trend is significant in the spring season only." They also admitted "the robustness of this springtime trend is in doubt" because the trend obtained from the other dataset was negative. For the conterminous United States, the two datasets showed "mostly small positive trends in most seasons" but none of these trends were statistically significant. Iskenderian and Rosen acknowledged they "cannot state with confidence that there has been a change in synoptic-scale temperature variance in the mid-troposphere over the United States since 1958."

Two years later, in a study based on daily maximum (max), minimum (min), and mean air temperatures (T) from 1062 stations of the U.S. Historical Climatology Network, Robeson (2002) computed the slopes of the relationships defined by plots of daily air temperature standard deviation vs. daily mean air temperature for each month of the year for the period 1948–1997. This protocol revealed, in Robeson's words, "for most of the contiguous USA, the slope of the relationship between the monthly mean and monthly standard deviation of daily Tmax and Tmin—the variance response—is either negative or near-zero." This means, as he described it, "for

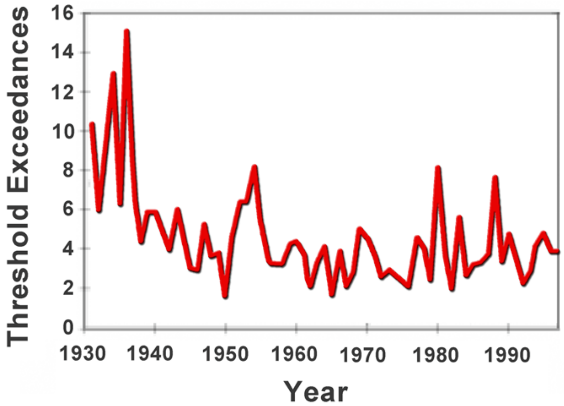

Figure 7.1.3.1. Heat wave exceedance threshold calculated as the number of days with a maximum temperature above the threshold for a 1.5% daily exceedance probability. The curve represents an average of 876 long-term stations in the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098.

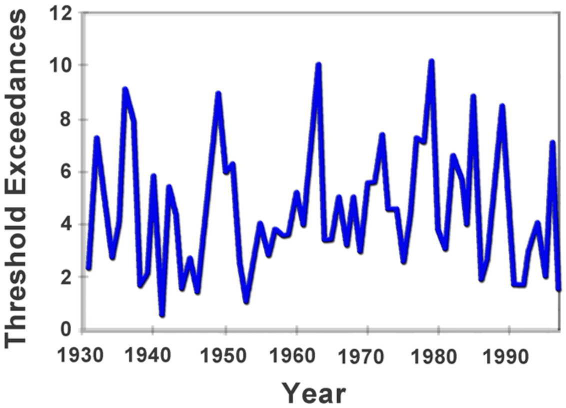

Figure 7.1.3.2. Cold wave exceedance threshold calculated as the number of days with a minimum temperature below the threshold for a 98.5% daily exceedance probability. The curve represents an average of 876 long-term stations from the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098..

most of the contiguous USA, a warming climate should produce either reduced air-temperature variability or no change in air-temperature variability.” He also reported the negative relationships are “fairly strong, with typical reductions in standard deviation ranging from 0.2 to 0.5°C for every 1°C increase in mean temperature.”

DeGaetano and Allen (2002b) created a Daily Historical Climatology Network for Extreme Temperature (HCN-XT) dataset (DeGaetano and Allen, 2002a), which they used to determine how both hot and cold temperature extremes—defined in terms of the number of exceedances of the 90th, 95th, and 99th%iles of their respective databases—have varied across the contiguous United States over a number of different time scales.

Over the period 1960–1996, DeGaetano and Allen determined “a large majority of stations show increases in warm extreme temperature exceedances,” which would seem to corroborate model-based claims. They also reported “about 20% of the stations experience significant increases in warm maximum temperature occurrence,” again in seeming vindication of model-based claims. Furthermore, they noted “similar increases in the number of ≥2 and ≥3 runs of extreme temperatures occur across the country,” apparently substantiating claims of an increasing frequency of deadly heat waves.

However, when the two scientists extended their analyses further back in time, they obtained quite different results. Adding another 30 years of data onto the front ends of their databases, DeGaetano and Allen discovered there were “predominantly decreasing warm exceedance trends across the country during the 1930–96 period.” They found “in the 1930–96 period 70% of the stations exhibit decreasing high extreme maximum temperature trends.”

DeGaetano and Allen also found “trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th%ile across the United States are strongly influenced by urbanization.” With respect to daily warm minimum temperatures, for example, the slope of the regression line fit to the data of a plot of the annual number of 95th%ile exceedances vs. year over the period 1960–96 was found to be +0.09 exceedances per year for rural stations, +0.16 for suburban stations, and +0.26 for urban stations, making the rate of increase in extreme warm minimum temperatures at urban stations nearly three times greater than the increase at rural stations less affected by growing urban heat islands. The rate of increase in the annual number of daily maximum temperature 95th%ile exceedances per year over the same time period was found to be 50% greater at urban stations than at rural stations. In spite of this vast uncorrected bias, when computed over the longer 1930–1996 period, 70% of all stations in the HCN-XT dataset exhibited “decreasing high extreme maximum temperature trends.”

DeGaetano and Allen’s findings clearly show extreme warm temperature events over the USA are no more prevalent currently than they were in the 1930s and may be even less prevalent now. Also, there is strong evidence implicating the growing influence of intensifying urban heat islands as being responsible for the apparent rapid increase in the mean annual temperatures for many locations over the last two decades of the twentieth century. Thus, even for the part of the world that may have experienced some net warming over the past 70 years, the warming is likely minimal.

Focusing on extreme temperatures experienced during heat waves, Redner and Petersen (2006) noted “almost every summer, there is a heat wave somewhere in the United States that garners popular media attention,” and it is only natural to wonder if global warming played a role in producing it. The two scientists set out to investigate “how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures,” after which they assessed the potential of global warming to produce such temperatures by comparing their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia.

The two researchers concluded “the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data.” They found they “cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures,” even with 126 years of real-world data. Such findings suggest it is not statistically justifiable to attribute any individual heat wave or “proliferation of record-breaking temperature events” to historical global warming, be it CO_2-induced or otherwise.

In an attempt to determine the role the planet’s mean temperature may have played in influencing temperature variability during the latter half of the twentieth century, Higgins *et al.* (2002) examined the influence of two important sources of Northern

Hemispheric climate variability—the El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation—on winter (Jan–Mar) daily temperature extremes over the conterminous United States from 1950 to 1999. With respect to the Arctic Oscillation, there was basically no difference in the number of extreme temperature days between its positive and negative phases. With respect to the ENSO phenomenon, however, Higgins *et al*. found during El Niño years, the total number of extreme temperature days decreased by approximately 10%, while during La Niña years they increased by approximately 5%. With respect to winter temperatures throughout the conterminous United States, therefore, the model-based contention that warmer global temperatures—such as are typically experienced during El Niño years—will produce more extreme weather conditions is unsupported, as Higgins *et al* found the opposite to be true.

Contrary to model projections, the research reported here concludes a warmer climate does not tend to produce a more variable climate. The data suggest a warmer climate may be less variable and less extreme, if any change occurs at all. The scientific literature does not support projections of more frequent and intense summer heat waves.

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7.1.4 Other Areas

This subsection highlights several peer-reviewed studies from various other regions of the globe (outside of Asia, Europe, and North America, examined in the preceding subsections) that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Starting with a long temporal view of the subject, Oppo *et al*. (1998) studied sediments from Ocean Drilling Project site 980 on the Feni Drift (55.5°N, 14.7°W) in the North Atlantic. Working with a core formed 500,000 to 340,000 years ago, they analyzed $\delta^{18}O$ and $\delta^{13}C$ obtained from benthic foraminifera and $\delta^{18}O$ obtained from planktonic foraminifera to develop histories of deep water circulation and sea surface temperature (SST), respectively. They discovered a number of persistent climatic oscillations with periods of 6,000, 2,600, 1,800, and 1,400 years that traversed the entire length of the sediment core record, extending through glacial and interglacial epochs alike. These SST variations, which were found to be in phase with deep-ocean circulation changes, were on the order of 3°C during cold glacial maxima but only 0.5 to 1°C during warm interglacials.

McManus *et al*. (1999), who also examined a half-million-year-old deep-sea sediment core from the eastern North Atlantic, reported similar findings. The authors noted significant SST oscillations throughout the record, and they too were of much greater amplitude during glacial periods (4 to 6°C) than during interglacials (1 to 2°C). Likewise, in another study of a half-million-year-long sediment core from the same region, Helmke *et al*. (2002) found the most stable of all climates held sway during what they called "peak interglaciations" or periods of greatest warmth. The temperatures in each of the interglacials that preceded our current interglacial were warmer than the present one, and by an average temperature in excess of 2°C, as determined by Petit *et al*. (1999). Thus, even if Earth were to continue its recent recovery from the global chill of the Little Ice Age, that warming likely would cause a decrease in temperature variability, as evidenced by real-world data pertaining to the past half-million years.

Shifting the temporal focus to that of the past millennium, Cook *et al*. (2002) reported the results of a tree-ring study of long-lived silver pines on the West Coast of New Zealand's South Island. The chronology they derived provided a reliable history of Austral summer temperatures from AD 1200 to 1957, after which measured temperatures were used to extend the history to 1999. Cook *et al*. stated their reconstruction showed "there have been several periods of above and below average temperature that have not been experienced in the 20th century," indicating New Zealand climate was much less variable over the last century than it was over the prior 700 years.

Focusing on a finer temporal resolution, Ault *et al*. (2009) employed 23 coral δ^{18}O records from the Indian and Pacific Oceans to extend the observational record of decadal climate variability in the region to AD 1850–1990, noting "coral records closely track tropical Indo-Pacific variability on interannual to decadal timescales (Urban *et al*., 2000; Cobb *et al*., 2001; Linsley *et al*., 2008)." The seven scientists identified "a strong decadal component of climate variability" that "closely matches instrumental results from the 20th century." In addition, they noted the decadal variance was much greater between 1850 and 1920 than it was between 1920 and 1990. The researchers "infer that this decadal signal represents a fundamental timescale of ENSO variability" whose enhanced variance in the early half of the record "remains to be explained."

In a study designed to investigate the IPCC contention "that in the future the frequency of extreme temperature events and their magnitude will increase," Rusticucci and Barrucand (2004) investigated how such a claim might apply to Argentina, deriving trends of the mean, the standard deviation, and the extreme maximum and minimum daily temperatures over the period 1959–1998 based on "a deeply quality-controlled stations database." According to the two Argentine scientists, "the variable that presents the largest number of stations with observed significant trends is the minimum temperature in summer, where positive trend values were found at many stations over 4°C (100 yr)$^{-1}$." They also reported "the maximum temperature in summer presented strong negative values of the same magnitude in stations located in central Argentina." The researchers concluded "a large fraction of the area that yields most of the agricultural production of Argentina should result in reduced air temperature variability in the case of a warming climate, as is also shown by Robeson (2002) for the United States."

Rusticucci (2012) further examined the claim global warming will increase climatic variability, reviewing many studies that have explored this subject throughout the length and breadth of South America, particularly as it applies to daily maximum and minimum air temperatures. The Buenos Aires researcher found the most significant trends exist in the evolution of the daily minimum air temperature, with "positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature)," as well as negative trends in the cold extremes of the minimum temperature. She states this was the case "in almost all studies." By contrast, she writes, "on the maximum temperature behavior there is little agreement, but generally the maximum temperature in South America has decreased."

In general, over most of South America there has been a decrease in the extremeness of both daily maximum and minimum air temperatures, with the maximums declining and the minimums rising. These findings are beneficial, as Rusticucci notes cold waves and frost are especially harmful to agriculture, one of the main economic activities in South America. Cold waves and frost days were on the decline nearly everywhere throughout the continent during the warming of the twentieth century.

Alexander *et al*. (2006) developed what they call "the most up-to-date and comprehensive global picture of trends in extreme temperature." They analyzed results from a number of workshops held in data-sparse regions and high-quality station data supplied by numerous scientists from around the world, after which several seasonal and annual temperature indices for the period 1951–2003 were calculated and gridded, and trends in the gridded fields were computed and tested for statistical significance.

Alexander *et al*. report "over 70% of the land area sampled showed a significant increase in the annual occurrence of warm nights while the occurrence of cold nights showed a similar proportion of significant decrease," with some regions experiencing "a more than doubling of these indices." At the other end of the scale, they found only 20% of the land area sampled exhibited statistically significant changes, specifically noting "maximum temperature extremes have also increased but to a lesser degree." These findings, in the words of the researchers, "agree with earlier global studies (e.g., Jones *et al*., 1999) and regional studies (e.g., Klein Tank and Konnen, 2003; Manton *et al*., 2001; Vincent and Mekis, 2006; Yan *et al*., 2002), which imply that rather than viewing the world as getting hotter it might be more accurate to view it as getting less cold."

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7.1.5 Cold Weather Extremes

The global mean temperature trend, estimated by the UK Met Office, shows a lack of warming of Earth's climate during the past 16 years. In addition, there is mounting evidence of a recent increase in cold weather extremes in many parts of the world.

The brunt of recent cold weather extremes seems to have been borne by Europe, which has experienced extremely cold winters for the past six years. The latest round of cold European weather (in 2013) brought large amounts of snow in northern France, Germany, Belgium, and Poland. Berlin is reported to have experienced its coldest winter in 100 years. Also, Hungary and Poland reported excessive snow and bitterly cold weather in the month of March. Just last year (February 2012) most of eastern and Central Europe, including Belarus, Poland, Slovakia, and the Czech Republic, experienced severe cold weather, with low temperatures at some locales reaching -40°C and below. The cold weather caused several hundred deaths during February 2012 in the Czech Republic, Hungary, and Poland.

The winters of 2009–2010 and 2010–2011 were equally cold and snowy in parts of Europe and North America (Seager *et al*., 2010; Taws *et al*., 2011). In South America, winters have become colder during the past six years. In July 2007, parts of Argentina reported low temperatures at -25°C, and snow fell in Buenos Aires in July 2007 – the city's first snowfall since 1918. July 2013 was significantly colder in the southern regions of South America, with snow reported in more than 75 locales in Argentina and southern Brazil during the week of July 20–25, 2013.

In tropical Asia, winters also have become colder in the past ten years. The severity of the cold winter of 2002–2003 was felt as far south as Vietnam and Bangladesh, where several hundred people died of exposure. Also, winters in Northern India have become colder in the past six years or so. The past winter (December 2012–January 2013) brought several low temperature records (0°C to -5°C) in parts of NW India and in many large cities such as New Delhi, which endured its coldest January in 40 years. Several hundred people died from exposure to the cold weather there as well, as houses in North India are not equipped with heating or good insulation.

The media rarely mention such extreme cold weather events, and the past few years have brought relatively few studies on cold winters. Most such publications have been by European meteorologists and climate scientists. Among the papers reported in recent literature are those by Benested (2010), Cattiauax *et al*. (2010), Haigh (2010), Lockwood *et al*. (2011), Petoukhov and Semenov (2010), Sirocko *et al*. (2012), Wang *et al*. (2010), and Woollings *et al*. (2010). Many of these papers suggest reduced solar activity played a prominent role in the observed colder winters.

Some solar scientists are investigating the possibility of the Sun entering into a Grand Solar Minimum (GSM), which could manifest itself within two decades (Lockwood *et al*., 2011). How an approaching GSM might impact Earth's climate is being studied extensively. Papers by Schindell *et al*., (2001) and others discussed the impact of past low solar activity on regional and global climate. During the last GSM, known popularly as the Maunder Minimum, Earth's climate underwent what has come to be known in climatic terms as the Little Ice Age (LIA), a period that brought the coldest temperatures of the Holocene, or current interglacial, in which we live. Lasting about 200 years (approximately 1650–1850), the brunt of the LIA was felt in Europe, which experienced long and extreme winters and cooler summers. Soon and Yaskell (2003) provide a comprehensive discussion of the climatic impact of the Maunder Minimum. Whether the Sun is indeed approaching a new Grand Solar Minimum, however, remains to be seen.

Along with a recent spate of cold temperature extremes experienced across the globe, record snowfall has occurred in many places, especially in the Northern Hemisphere. The winter of December 2012–March 2013 brought several large snowstorms across Europe and North America. The first two weeks of March saw several heavy to very heavy snowfalls in Northern France, Germany, and Belgium, with snowfall amounts reaching 25cm and more in many places. Over North America, the winter of 2012–2013 was long and snowy from the southwestern U.S. to the upper Midwest. A February 26–27 snowstorm dumped more than 45cm of snow on Amarillo, Texas. The same storm dumped more than 30 cm of snow on parts of central Ontario and Toronto as it moved in a SW-NE track. In early to mid-March, snowfalls varying from 20cm to 30cm fell in several states from Colorado to Minnesota. On the Canadian Prairies, the week of March 17–24 saw heavy snowfalls (15–25cm) in parts of Alberta and Saskatchewan.

Other examples of recent heavy snowfall include:

Winter 2011–2012:

Alaska. Some of the heaviest snowfalls ever recorded fell in January 2012. The fishing community of Cordova (east side of Prince William Sound) received close to 450cm of snow between November 2011 and January 2012. At Valdez, more than 350cm of snow fell in the first two weeks of January.

Canadian Rockies. The Canadian Rockies experienced some of the region's heaviest-ever recorded snowfalls in many areas. Sunshine Village (a popular ski resort on the Alberta/British Columbia border) set an all-time record with more than 915cm of snow by March 25. At Mount Norquay (near Banff, Alberta) more than 900cm of snow fell from November to March. At Ferni Alpine Resort (British Columbia) more than 1,000cm of snow fell during the 2011–2012 winter season, a record.

Europe. One of the most severe winters in Eastern Europe brought snowfalls of 25cm and more. In the eastern Adriatic Sea, more than 35cm of snow fell near Montenegro on February 10–11.

Japan. Snowfall several tens of cm deep fell in parts of Japan during February 12–14, 2012.

Winter 2010–2011: More than 80cm of snow fell in a two-day period (5–6 December 2010) in London, Ontario (Canada). Montreal received more than 30cm (December 6–7).

Winter 2009-2010: The largest snow cover extent in the history of the contiguous United States occurred in December 2009. The mid-Atlantic cities of Baltimore, Philadelphia, and Washington, DC had their snowiest winters ever (each received more than 150cm of snow). The winter of 2009–2010 was the snowiest since 1977–78 in the Northern Hemisphere. Khandekar (2010) reported additional snowfall and cold weather records during the previous 10 years.

The latest snow cover data archived at the Rutgers Northern Hemisphere snow data center (US) are shown in Table 7.1.5.1. The winter of 2012–2013 was the fourth snowiest in Northern Hemisphere history. Five winter seasons (December–February) since 2000 are among the top six winters for snow accumulation. If the November snow data were included in the table, this past winter would be the second snowiest winter during the past 40 years.

Winter snow accumulation in the Northern Hemisphere has been increasing in recent years. Such observations run counter to model projections suggesting there should be less snowfall occurring in response to CO_2-induced global warming.

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Table 7.1.5.1. The top 15 winter season snowfall accumulation totals in the Northern Hemisphere.

Season (Dec–Feb)	Snow Accumulation (Millions km^2)
1977–78	48.403
2009–10	47.507
2010–11	47.183
2012–13	47.150
2007–08	46.910
2002–03	46.830
1978–79	46.730
1984–85	46.722
1985–86	46.577
1971–72	46.517
1970–71	46.317
1968–69	46.297
1966–67	46.073
1981–82	45.810
2011–12	45.803

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7.2 Heat Waves

In response to an increase in mean global air temperature, the IPCC contends there will be more frequent and severe extremes of various weather phenomena, including more frequent and extreme heat waves. In its *Fifth Assessment Report*, the IPCC states “models also project increases in the duration, intensity and spatial extent of heat-waves and warm spells for the near term” (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). Furthermore, they suggest an anthropogenic influence is already underway, stating “we now conclude that it is likely that human influence has significantly increased the probability of some observed heat waves” (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). Although much of the material in the preceding section of this chapter (Section 7.1, Temperature) reveals the IPCC claims on heat waves have little support in the scientific literature, this section examines additional studies that also explain why the IPCC projections are likely wrong.

Deng *et al*. (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 to examine trends in heat waves in the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. The three Chinese researchers report their study area experienced a mean annual warming trend with slight decreasing trends in spring and summer temperatures. They also found extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that “the frequencies of heat waves and long heat waves in the recent years were no larger than the late 1950s and early 1960s.” They observed, “coupled with the extreme low frequency in the 1980s, heat waves and long heat waves showed a slight linear decreasing trend in the past 50 years.” They noted the most recent frequency of heat waves “does not outnumber 1959 or 1961” and “none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003.”

Deng *et al*. concluded, citing Tan *et al*. (2007), “compared with the 1950s and 1960s, short heat waves instead of long heat waves have taken place more often,” which, as they describe it, “is desirable, as longer duration leads to higher mortality.”

Redner and Petersen (2006) investigated “how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures.” They compared their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia. The results of their mathematical analysis led them to conclude “the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data.” They also stated they “cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures,” even with 126 years of data.

Fischer *et al*. (2007) and Robock *et al*. (2000) may provide some insight into why the models are failing in their heat wave projections.

Fischer *et al*. conducted regional climate simulations, both with and without land-atmosphere coupling, for the major European summer heat waves of 1976, 1994, 2003, and 2005. The authors found during all simulated heat wave events, "soil moisture-temperature interactions increase the heat wave duration and account for typically 50–80% of the number of hot summer days," noting "the largest impact is found for daily maximum temperatures," which were amplified by as much as 2-3°C in response to observed soil moisture deficits in their study.

Robock *et al.* developed a massive collection of soil moisture data from more than 600 stations spread across a variety of climatic regimes (including the former Soviet Union, China, Mongolia, India, and the United States). They found "for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." This counterintuitive finding was confirmed by Robock *et al.* (2005) and Li *et al.* (2007), the latter noting when exposed to elevated concentrations of atmospheric CO_2, "many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere," so "more water is likely to be stored in the soil or [diverted to] runoff." Gedney *et al.* (2006) confirmed the latter phenomenon. Pearce (2006) quoted Gedney saying "climate change on its own would have slightly reduced runoff, whereas the carbon dioxide effect on plants would have increased global runoff by about 5%," with the combined effect of the two competing phenomena leading to the 3–4% flow increase actually observed.

In light of the complementary global soil moisture and river runoff observations, it would appear, in general, the anti-transpiration effect of the historical rise in the air's CO_2 content has more than compensated for the soil-drying effect of global warming. Fischer *et al.* (2007) found soil moisture depletion greatly augments both the intensity and duration of summer heat waves, while Robock *et al.* (2000, 2005) and Li *et al.* (2007) found global soil moisture has increased over the past half-century, likely as a result of the anti-transpiration effect of atmospheric CO_2 enrichment—as Gedney *et al.* (2006) also have found to be the case with closely associated river runoff. Thus the increase in soil moisture caused by rising atmospheric CO_2 concentrations will tend to decrease both the intensity and duration of summer heat waves as time progresses. That relationship may explain why historic heat waves in locations such as Philadelphia and the Three Gorges area of China have not increased in response to what the IPCC often refers to as the unprecedented warming of the late twentieth and early twenty-first centuries.

Jeong *et al.* (2010) observe modeling studies in the IPCC's *Fourth Assessment Report* (AR4) suggest future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming. Jeong *et al.* investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments," where land surface processes were calculated by the Community Land Model (version 3) described by Oleson *et al.* (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables.

Their calculations revealed "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included," and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapo-transpiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." The scientists found "the greening also tends to reduce the frequency and duration of heat waves."

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7.3 Fire

According to model-based predictions, larger and more intense wildfires will become more frequent as a result of CO_2-induced global warming. Many scientists have begun to search for a link between fire and climate, often examining past trends to see if they support the models' projections. The following section examines what has been learned in this regard, beginning with a review of studies conducted in North America and ending with a discussion of the planet as a whole.

Campbell and Campbell (2000) analyzed pollen and charcoal records obtained from sediment cores retrieved from three small ponds—South Pond (AD 1655–1993), Birch Island Pond (AD 1499–1993), and Pen 5 Pond (400 BC–AD 1993)—in Canada's Elk Island National Park, which covers close to 200 km^2 of the Beaver Hills region of east-central Alberta. "Counter to the intuitive increase in fire activity with warmer and drier climate," the Canadian researchers reported, "declining groundwater levels during the Medieval Warm Period [MWP] allowed the replacement of substantial areas of shrub birch with the less fire-prone aspen, causing a decline in fire frequency and/or severity, while increasing carbon storage on the landscape," as implied by their Pen 5 Pond data. They concluded this scenario "is likely playing out again today," as all three of the sites they studied "show historic increases in *Populus* pollen and declines in charcoal."

Carcaillet *et al*. (2001) developed high-resolution charcoal records from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada. The scientists determined whether vegetation change or climate change was the primary determinant of changes in fire frequency, comparing their fire history with hydroclimatic reconstructions derived from $\delta^{18}O$ and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago, when it was significantly warmer than it is today, they reported "fire intervals were double those in the last 2,000 years," meaning fires were only half as frequent throughout the earlier, warmer period as they were during the subsequent, cooler period. They also determined "vegetation does not control the long-term fire regime in the boreal forest," but instead, "climate appears to be the main process triggering fire." In addition, they report "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al*., 1990; Larsen, 1997; Weir *et al*., 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al*., 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)." The scientists concluded a "future warmer climate is likely to be less favorable for fire ignition and spread in the east Canadian boreal forest than over the last 2 millennia."

Le Goff *et al*. (2007) investigated "regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years vs. non-fire years in the Waswanipi area of northeastern Canada [49.5–50.5°N, 75–76.5°W], and the long-term relationship with large-scale climate variations ...

using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps." Their analysis showed instead of the interval of time between wildfires shortening as time progressed and the climate warmed, there was "a major lengthening of the fire cycle," which expanded "from 99 years before 1940 to 282 years after 1940." In addition, Le Goff *et al*. noted "in the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 [or the "end of the Little Ice Age," as they describe it] (Bergeron and Archambault, 1993; Larsen, 1996) and a further decrease after 1940 (Bergeron *et al*., 2001, 2004a,b, 2006)."

Similar findings were reported by Lauzon *et al*. (2007) while investigating the fire history of a 6,480-km^2 area located in the Baie-Des-Chaleurs region of Gaspesie at the southeastern edge of Quebec "using Quebec Ministry of Natural Resource archival data and aerial photographs combined with dendrochronological data." Coincident with the 150-year warming that led to the demise of the Little Ice Age and the establishment of the Current Warm Period, the three researchers reported there was "an increase in the fire cycle from the pre-1850 period (89 years) to the post-1850 period (176 years)," and "both maximum and mean values of the Fire Weather Index decreased statistically between 1920 and 2003." During the latter period, they observed, "extreme values dropped from the very high to high categories, while mean values changed from moderate to low categories." In contrast with model projections, and in this particular part of the world, twentieth century global warming has led to a significant decrease in the frequency of forest fires, as weather conditions conducive to their occurrence have become less prevalent and extreme.

Girardin *et al*. (2006) hypothesized "human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures." They noted "climate change therefore could cause longer fire seasons (Wotton and Flannigan, 1993), with greater fire activity and greater incidence of extreme fire activity years (Colombo *et al*., 1998; Parker *et al*., 2000)." To provide a more rigorous test of the hypothesis than could be provided by the historical observational record, they determined it should be placed in a much longer context. Girardin *et al*. inferred past area burned in Ontario for the period AD 1781–1982 by regressing tree-ring chronologies against actual area burned data and developing transfer functions they used "to estimate annual area burned at times during which there were no instrumental data."

The three researchers reported "while in recent decades area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s." The researchers further noted "the most recent increase in area burned in the province of Ontario was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s–1960s)," despite the fact "humans during the past decades have been an important source of fire ignition." Consequently, although according to theory "one should expect greater area burned in a changing climate," their findings revealed just the opposite.

The robust nature of the Canadian scientists' findings is substantiated by "numerous studies of forest stand age distributions [an independent way of assessing the matter] across the Canadian boreal forest [a larger area than Ontario alone] [that] report lower fire activity since circa 1850 (Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Bergeron *et al*., 2001, 2004a, 2004b; Tardif, 2004)."

Beaty and Taylor (2009) developed a 14,000-year record of fire frequency based on high-resolution charcoal analysis of a 5.5-m-long sediment core extracted from Lily Pond (39°3'26"N, 120°7'21"W) in the General Creek Watershed on the west shore of Lake Tahoe in the northern Sierra Nevada in California (USA), as well as a 20-cm-long surface core that "preserved the sediment-water interface."

They found "fire episode frequency was low during the Lateglacial period but increased through the middle Holocene to a maximum frequency around 6500 cal. yr BP," which "corresponded with the Holocene temperature maximum (7000–4000 cal. yr BP)." Thereafter, as the temperature gradually declined, so too did fire frequency, except for a multicentury aberration they described as "a similar peak in fire episode frequency [that] occurred between c. 1000 and 600 cal. yr BP during the 'Medieval Warm Period,'" which they indicated was followed by an interval "between c. 500 and 200 cal. yr BP with few charcoal peaks [that] corresponded with the so-called 'Little Ice Age.'" Arriving at the present, they find the "current fire episode frequency on the west shore of Lake Tahoe is at one of its lowest points in at least the last 14,000 years."

A contrary example, where warming does appear to have enhanced fire occurrence, is provided by Pierce *et al*. (2004), who dated fire-related sediment deposits in alluvial fans in central Idaho, USA, in a research program designed to reconstruct Holocene fire history in xeric ponderosa pine forests and to look for links to past climate change. This endeavor focused on tributary alluvial fans of the South Fork Payette (SFP) River area, where fans receive sediment from small but steep basins in weathered batholith granitic rocks conducive to post-fire erosion. Altogether, they obtained 133 AMS ^{14}C-derived dates from 33 stratigraphic sites in 32 alluvial fans. In addition, they compared their findings with those of Meyer *et al*. (1995), who had earlier reconstructed a similar fire history for nearby Yellowstone National Park in Wyoming, USA.

Pierce *et al*.'s work revealed "intervals of stand-replacing fires and large debris-flow events are largely coincident in SFP ponderosa pine forests and Yellowstone, most notably during the 'Medieval Climatic Anomaly' (MCA), ~1,050-650 cal. yr BP." They also noted "in the western USA, the MCA included widespread, severe miltidecadal droughts (Stine, 1998; Woodhouse and Overpeck, 1998), with increased fire activity across diverse northwestern conifer forests (Meyer *et al*., 1995; Rollins *et al*., 2002)."

Following the Medieval Warm Period and its frequent large-event fires was the Little Ice Age, when, as Pierce *et al*. described it, "colder conditions maintained high canopy moisture, inhibiting stand-replacing fires in both Yellowstone lodgepole pine forests and SFP ponderosa pine forests (Meyer *et al*., 1995; Rollins *et al*., 2002; Whitlock *et al*., 2003)." Subsequently, they reported, "over the twentieth century, fire size and severity have increased in most ponderosa pine forests," which they suggest may be largely due to "the rapidity and magnitude of twentieth-century global climate change."

Westerling *et al*. (2006), who compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydroclimatic and land-surface data, reached similar conclusions. Their findings are succinctly summarized by Running (2006) in an accompanying Perspective, where he wrote "since 1986, longer warmer summers have resulted in a fourfold increase of major wildfires and a sixfold increase in the area of forest burned, compared to the period from 1970 to 1986," noting also "the length of the active wildfire season in the western United States has increased by 78 days, and that the average burn duration of large fires has increased from 7.5 to 37.1 days." In addition, he states, "four critical factors—earlier snowmelt [by one to four weeks], higher summer temperatures [by about 0.9°C], longer fire season, and expanded vulnerable area of high-elevation forests—are combining to produce the observed increase in wildfire activity."

Schoennagel *et al*. (2007) investigated "climatic mechanisms influencing subalpine forest fire occurrence in western Colorado, which provide a key to the intuitive link between drought and large, high-severity fires that are keystone disturbance processes in many high-elevation forests in the western United States," focusing on three major climatic oscillations: the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO).

They found "fires occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO and [the Pacific Decadal Oscillation (PDO)] and during positive departures from [the mean Atlantic Multidecadal Oscillation (AMO)] index," while "at longer time scales, fires exhibited 20-year periods of synchrony with the cool phase of the PDO, and 80-year periods of synchrony with extreme warm (positive) phases of the AMO." In addition, they note "years of combined positive AMO and negative ENSO and PDO phases represent 'triple whammies' that significantly increased the occurrence of drought-induced fires." On the other hand, they observed "drought and wildfire are associated with warm phases of ENSO and PDO in the Pacific Northwest and northern Rockies while the opposite occurs in the Southwest and southern Rockies," citing the findings of Westerling and Swetnam (2003), McCabe *et al*. (2004), and Schoennagel *et al*. (2005). Schoennagel *et al*. thus concluded "there remains considerable uncertainty regarding the effects of CO_2-induced warming at regional scales." Nevertheless, they reported, "there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies" in the region of their study, high-elevation western U.S. forests, though such a consequence should not necessarily be viewed as a response to CO_2-induced global warming.

Brunelle *et al*. (2010) collected sediments during the summers of 2004 and 2005 from a drainage basin located in southeastern Arizona (USA) and north-eastern Sonora (Mexico), from which samples were taken "for charcoal analysis to reconstruct fire history" as well as pollen data to infer something about climate.

According to the U.S. and Mexican researchers, "preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity," and the results from the fire reconstruction "show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly." During this latter period, from approximately AD 900 to 1260, "background charcoal reaches the highest level of the entire record and fire peaks are frequent," and "the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al*., 2004)."

Brunelle *et al*. speculated if the region of their study warms in the future, "the role of fire in the desert grasslands is likely to change," such that "warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires, similar to >5000 cal yr BP."

Pitkanen *et al*. (2003) constructed a Holocene fire history of dry heath forests in eastern Finland on the basis of charcoal layer data obtained from two small mire basins and fire scars on living and dead pine trees. This work revealed a "decrease in fires during climatic warming in the Atlantic chronozone (about 9000–6000 cal. yr. BP)," prompting them to conclude "the very low fire frequency during the Atlantic chronozone despite climatic warming with higher summer temperatures, is contrary to assumptions about possible implications of the present climatic warming due to greenhouse gasses." Thereafter, the researchers observed an increase in fire frequency at the transition between the Atlantic and Subboreal chronozones around 6000 cal. yr. BP, noting "the climatic change that triggered the increase in fire frequency was cooling and a shift to a more continental climate." In addition, they reported the data of Bergeron and Archambault (1993) and Carcaillet *et al*. (2001) from Canada suggest much the same thing; i.e., a decrease in boreal forest fires during periods of greater warmth. Consequently, "as regards the concern that fire frequency will increase in [the] near future owing to global warming," the researchers say their data "suggest that fires from 'natural' causes (lightning) are not likely to increase significantly in eastern Finland and in geographically and climatically related areas."

Wallenius *et al*. (2011) observed "the effect of ongoing climate change on forest fires is a hotly debated topic," with many "experts" arguing "the climatic warming in the 20th and 21st century has resulted and will result in an increase in forest fires." Against this backdrop Wallenius *et al*. set out to "add information about forest fire history of the as-yet poorly studied *Larix*-dominated forests of central Siberia by means of high-precision dendrochronological dating of past fires."

Studying the northern part of the Irkutsk district of central Siberia (centered at approximately 60.75°N, 107.75°E) in areas "untouched by modern forestry and agriculture," where "population density is low, with less than 0.1 inhabitant per square kilometer," the group of Finnish, Panamanian, and Russian researchers determined "in the 18th century, on average, 1.9% of the forests burned annually, but in the 20th century, this figure was only 0.6%," and "the fire cycles for these periods were 52 and 164 years, respectively." In addition, they reported "a further analysis of the period before the enhanced fire control program in the 1950s revealed a significant lengthening in the fire cycle between the periods 1650–1799 and 1800–1949, from 61 to 152 years, respectively." They noted "a similar phenomenon has been observed in Fennoscandia, southern Canada and the western United States, where the annually burned proportions have decreased since the 19th century (Niklasson and Granstrom, 2000; Weir *et al*., 2000; Heyerdahl *et al*., 2001; Bergeron *et al*., 2004b)." They also found "in these regions, the decrease has been mostly much steeper, and the current fire cycles are several hundreds or thousands of years."

Turner *et al*. (2008) analyzed micro-charcoal, pollen, and stable oxygen isotope ($\delta^{18}O$) data obtained from sediment cores extracted from two crater lake basins in central Turkey, from which they reconstructed synchronized fire, vegetation, and climate histories that extend back in time more than 15,000 years. The authors determined "climatically-induced variation in biomass availability was the main factor controlling the timing of regional fire activity during the Last Glacial-Interglacial climatic transition, and again during Mid-Holocene times, with fire frequency and magnitude increasing during wetter climatic phases." In addition, they reported spectral analysis of the Holocene part of the record "indicates significant cyclicity with a periodicity of ~1500 years that may be linked with large-scale climate forcing."

McAneney *et al*. (2009) assembled a much different database for evaluating the global warming/fire relationship as it pertains to Australia. The primary source of information for their study was the "Risk Frontiers' disaster database of historic building losses—PerilAUS—which provides a reasonably faithful testimony of national building losses from 1900," with additional information provided by the Insurance Council of Australia's database of significant insured losses.

The three researchers noted "the annual aggregate numbers of buildings destroyed by bushfire since 1926 ... is 84," but "most historical losses have taken place in a few extreme fires." Nevertheless, they observed "the most salient result is that the annual probability of building destruction has remained almost constant over the last century," even in the face of "large demographic and social changes as well as improvements in fire fighting technique and resources."

The researchers restated this finding many times: (1) "the historical evidence shows no obvious trend," (2) "the likelihood of losing homes to bushfire has remained remarkably stable over the last century with some building destruction expected in around 55% of years," (3) "this same stability is also exhibited for the bigger events with an annual probability of losing more than 25 or 100 homes in a single week remaining around 40% and 20% respectively," and (4) "the statistics on home destruction have remained obstinately invariant over time." In addition, McAneney *et al*. noted "Australia's population has increased from around 4 to 20 million over the last century," and therefore we might logically have expected "the likelihood of bushfire losses to have increased with population or at least with the population living immediately adjacent to bushlands." McAneney *et al*. concluded, "despite predictions of an increasing likelihood of conditions favoring bushfires under global climate change, we suspect that building losses due to bushfires are unlikely to alter materially in the near future."

Although specific areas of the planet experienced both significant increases and decreases in land area burned over the last two or three decades of the twentieth century, as illustrated in the materials reviewed above, what is the case for the world as a whole; i.e., what is the net result of the often opposite wildfire responses to warming that are typical of different parts of the planet?

Girardin *et al*. (2009) investigated "changes in wildfire risk over the 1901–2002 period with an analysis of broad-scale patterns of drought variability on forested eco-regions of the North American and Eurasian continents." The seven scientists reported "despite warming since about 1850 and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so (e.g. Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Lehtonen and Kolstrom, 2000; Bergeron *et al*., 2001, 2004a,b; Mouillot and Field, 2005)." They found "this holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia."

With respect to this long-term "diminishing fire activity," Girardin *et al*. observed "the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction." That role would appear to be one of reducing fire activity. To emphasize that point and provide still more evidence for it, the authors noted, "the fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control."

Riano *et al*. (2007) conducted "an analysis of the spatial and temporal patterns of global burned area with the Daily Tile US National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer Pathfinder 8 km Land dataset between 1981 and 2000." As demonstrated previously, for several areas of the world this investigation revealed there were indeed significant upward trends in land area burned. Some parts of Eurasia and western North America, for example, had annual upward trends as high as 24.2 pixels per year, where a pixel represents an area of 64 km^2. These increases in burned area, however, were offset by equivalent decreases in burned area in tropical Southeast Asia and Central America. Consequently, observed Riano *et al*., "there was no significant global annual upward or downward trend in burned area." They also noted "there was also no significant upward or downward global trend in the burned area for any individual month." In addition, they found "latitude was not determinative, as divergent fire patterns were encountered for various land cover areas at the same latitude."

In one additional paper providing a global view of the subject, but over a longer time scale, Marlon *et al*. (2008) observed "large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes," and "climate-change projections indicate that we will be moving quickly out of the range of the natural variability of the past few centuries." In an effort to see what the global wildfire "range of natural variability" actually has been, Marlon *et al*. used "sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning [over] the past two millennia."

The international team of researchers reported "global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870," after which it "declined abruptly." In terms of attribution, they said the initial long-term decline in global biomass burning was due to "a long-term global cooling trend," while they suggested the rise in fires that followed was "linked to increasing human influences." With respect to the final decline in fires that took place after 1870, however, they noted it occurred "despite increasing air temperatures and population." As for what may have overpowered the tendency for increased global wildfires that would "normally" have been expected to result from the global warming of the Little Ice Age-to-Current Warm Period transition, the nine scientists attributed "reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management."

Evidence from prior centuries suggests global warming may indeed have had a tendency to promote wildfires on a global basis (since global cooling had a tendency to reduce them), but technological developments during the industrial age appear to have overpowered this natural tendency. It appears humans have become a dominant factor leading to a decrease in global wildfires over the past century and a half. Although one can readily identify specific parts of the planet that have experienced significant increases or decreases in land area burned over the past several decades, for the globe as a whole there has been no relationship between rising temperatures and total area burned over this latter period.

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7.4 Drought

One of the many assumed dangers of global warming is the predicted propensity for rising temperatures to produce more frequent, more severe, and longer-lasting droughts almost everywhere on Earth. In its most recent assessment report, the IPCC presents the following statements regarding the attribution of historic drought to human-induced global warming:

> While the [*Fourth Assessment Report*] concluded that it is more likely than not that anthropogenic influence has contributed to an increase in the droughts observed in the second half of the 20th century, an updated assessment of the observational evidence indicates that the AR4 conclusions regarding global increasing trends in hydrological droughts since the 1970s are no longer supported. Owing to the low confidence in observed large-scale trends in dryness combined with difficulties in distinguishing decadal-scale variability in drought from long term climate change we now conclude there is low confidence in the attribution of changes in drought over global land since the mid-20th century to human influence (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 31).
>
> The current assessment does not support the [*Fourth Assessment Report*] conclusions regarding global increasing trends in droughts but rather concludes that there is not enough evidence at present to suggest high confidence in observed trends in dryness. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 61).

Although the IPCC has revised downward its confidence in the attribution of historical drought to rising CO_2 emissions, it is doing so because the IPCC claims it has little confidence in the observed data trends and not enough data exist to validate its model-based theory on drought.

Section 7.4 presents a comprehensive analysis of the observational data on drought, demonstrating there exists a large body of peer-reviewed science that invalidates the model-based claims of global warming causing more drought.

7.4.1 Africa

Data presented in numerous peer-reviewed studies do not support the model-based claim CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Africa.

In “A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s," Lau *et al*. (2006) explored "the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs [coupled general circulation models] that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4." The scientists examined 19 CGCMs, each of which was "driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions." The work revealed "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, the scientists reported "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events."

Since all 19 CGCMs used in preparing the IPCC's *Fourth Assessment Report* were unable to adequately simulate the basic characteristics of what Lau *et al*. call one of the past century's "most pronounced signals of climate change," this failure of what they call an "ideal test" for evaluating the models' abilities to accurately simulate "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" suggests extreme caution in relying on any of the models' output as a guide to the future. Even though the models were "driven by combinations of realistic prescribed external forcing," they could not properly simulate even the recent past.

Shifting attention to instrumental and proxy drought records, Nicholson (2001) reported in a review of information pertaining to the past two centuries there has been "a long-term reduction in rainfall in the semi-arid regions of West Africa" that has been "on the order of 20 to 40% in parts of the Sahel." Describing the phenomenon as "three decades of protracted aridity," she observed "nearly all of Africa has been affected ... particularly since the 1980s." Nevertheless, Nicholson reported "rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented" and "a similar dry episode prevailed during most of the first half of the 19th century," when much of the planet was still experiencing Little Ice Age conditions.

Therrell *et al*. (2006) developed "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This revealed "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995)," and "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They reported, for example, the year 1860 (the most droughty year of the entire period) was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, Therrel *et al*. reported "a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era." Consequently, for a large part of central southern Africa, the supposedly unprecedented global warming of the twentieth century did not result in an intensification of either extreme dry or wet periods. If anything, just the opposite appears to have occurred.

Esper *et al*. (2007) reported similar findings, noting "analysis of the PDSI [Palmer Drought Severity Index], a standardized measure of surface moisture conditions, revealed distinct 20th century aridity changes in vulnerable NW Africa, including a sharp downward trend towards drier conditions in the 1980s (Luterbacher *et al*., 2006)," but "a high-resolution long-term reconstruction that could place current conditions in the context of the past millennium is missing for N Africa," which the authors set out to develop. Esper *et al*. "re-use *Cedrus atlantica* tree-ring data generated in the 1980s (Glueck and Stockton, 2001) and combine these measurements with a major update collected in 2002," which "allows analysis of tree growth and instrumental data during the current drought episode in comparison to PDSI estimates back to AD 1049."

The six scientists reported "PDSI values were above average for most of the 1450–1980 period, which let recent drought appear exceptional." However, they found the long-term results they obtained indicated the "pluvial episode of the past millennium was preceded by generally drier conditions back to 1049," leading them to state the late twentieth century drought "appears more typical when associated with conditions before 1400." In addition, they concluded, the "ultimate drivers" for the medieval hydroclimate pattern that led to the earlier drought conditions in Morocco "seemed to be high solar irradiance and low volcanic forcings (Emile-Geay *et al*., 2007)."

Verschuren *et al*. (2000) developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on level and salinity fluctuations of a small crater-lake in Kenya, using data derived from diatom and midge assemblages retrieved from the lake's sediments. They found the Little Ice Age was generally wetter than the Modern Warm Period, but they identified three intervals of prolonged dryness within the Little Ice Age (1390–1420, 1560–1625, and 1760–1840). They note these "episodes of persistent aridity" were "more severe than any recorded drought of the twentieth century."

Holmes *et al.* (1997) probed 1,500 years into the past, reporting the African Sahel since the late 1960s has experienced "one of the most persistent droughts recorded by the entire global meteorological record."In a high-resolution study of a sediment sequence extracted from an oasis in the Manga Grasslands of northeast Nigeria, they determined "the present drought is not unique and that drought has recurred on a centennial to interdecadal timescale during the last 1500 years."

Russell *et al.* (2007) added another 500 years to the analysis, conducting lithostratigraphic analyses of sediment cores obtained from two crater lake basins in Western Uganda, Africa—Lake Kitagata (0°03'S, 29°58'E) and Lake Kibengo (0°04.9'S, 30°10.7'E)—spanning the past two millennia. Among other things, Russell *et al*. reported "variations in sedimentation and salt mineralogy of hypersaline Lake Kitagata, and a succession of fine-grained lake sediments and peat in the freshwater Lake Kibengo, suggest century-scale droughts centered on AD ~0 [and] ~1100."

Discussing what they called the "broader climatic implications" of their findings, the three researchers reported "based on comparison of proxy water-balance records from Lakes Edward (Russell *et al*., 2003; Russell and Johnson, 2005), Naivasha (Verschuren *et al*., 2000), Turkana (Halfman *et al*., 1994), and Tanganyika (Alin and Cohen, 2003), Russell *et al*. (2003) argued that drought around 2000 years ago (AD ~0) affected 'much, if not all, of equatorial Africa.'" Similarly, they observed, "Verschuren (2004) argued that drought centered on AD 1150 affected much of the region, a hypothesis supported by Russell and Johnson (2005)." Consequently, and in light of their similar, newer results, the three scientists concluded "droughts at AD ~0 and ~1150"—which roughly mark the midpoints of the Roman and Medieval Warm Periods, respectively—"do appear to have affected much of equatorial Africa."

Russell and Johnson (2005) derived a detailed precipitation history from sediment cores retrieved from Lake Edward, the smallest of the great rift lakes of East Africa, located on the border that separates Uganda and the Democratic Republic of the Congo. They discovered from the start of the record almost 5,500 years ago until approximately 1,800 years ago, there was a long-term trend toward progressively more arid conditions, after which there followed a "slight trend" toward wetter conditions that has persisted to the present. Superimposed on these long-term trends were major droughts of "at least century-scale duration," centered at approximately 850, 1,500, 2,000, and 4,100 years ago.

The studies cited here make clear the need for long-term (millennial-scale) records of climatic and meteorological phenomena in order to determine how exceptional twentieth century changes in their characteristics might be, which can help determine whether there is compelling reason to attribute such changes to historical increases in the atmospheric concentrations of greenhouse gases. For Africa, real-world evidence suggests the global warming of the past century or so has not led to a greater frequency or severity of drought in that part of the world. Even the continent's worst drought in recorded meteorological history does not seem to have been any worse (in fact, it was much milder) than droughts that occurred in the historic past. There is little reason to expect global warming to lead to more frequent or severe droughts in Africa.

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Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

7.4.2 Asia

As noted in the introduction to this Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Asia.

Using a multimodel approach developed previously (Wang *et al*., 2009), Wang *et al*. (2011) employed four physically based land surface hydrology models driven by an observation-based three-hourly meteorological dataset to simulate soil moisture over China for the period 1950–2006, deriving monthly values of total column soil moisture from which they calculated agricultural drought severities and durations. The authors reported "for drought areas greater than 150,000 km^2 and durations longer than three months, a total of 76 droughts were identified," and "regions with downward trends were larger than those with upward trends (37% versus 26% of the land area)," implying "over the period of analysis, the country has become slightly drier in terms of soil moisture."

Wang *et al*.'s findings are not proof of a CO_2-induced temperature link, nor do they imply an increase in future drought. Any suggestion of a link between drought and global warming is unique to the Wang *et al.* study, perhaps because their drought calculations are derived from models simulating soil moisture as opposed to measuring it. With respect to the future, Wang *et al*. report "climate models project that a warmer and moister atmosphere in the future will actually lead to an enhancement of the circulation strength and precipitation of the summer monsoon over most of China (e.g., Sun and Ding, 2010) that will offset enhanced drying due to increased atmospheric evaporative demand in a warmer world (Sheffield and Wood, 2008)."

Tao and Zhang (2011) provide some support for this statement. Using the Lund-Potsdam-Jena Dynamic Global Vegetation Model, they concluded the net effect of physiological and structural vegetation responses to expected increases in the air's CO_2 content will lead to "a decrease in mean evapotranspiration, as well as an increase in mean soil moisture and runoff across China's terrestrial ecosystem in the 21st century," which should act to lessen, or even offset, the "slightly drier" soil moisture conditions modeled by Wang *et al*.

In other studies examining drought trends in Asia—and China in particular—Paulsen *et al*. (2003) employed high-resolution stalagmite records of $\delta^{13}C$ and $\delta^{18}O$ from Buddha Cave "to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." Their record began in the depths of the Dark Ages Cold Period, which ended approximately AD 965 with the commencement of the Medieval Warm Period, and continued to approximately AD 1475, whereupon the Little Ice Age set in and held sway until about AD 1825, after which the warming responsible for the Modern Warm Period began.

With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet. It was followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Modern Warm Period. Paulsen *et al*.'s data also revealed other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture, and they attributed most of these higher-frequency cycles to solar phenomena. The authors concluded the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

The authors' data indicated Earth's climate is determined by a conglomerate of cycles within cycles, all of which are essentially independent of the air's CO_2 concentration. The data also demonstrated the multicentury warm and cold periods of the planet's millennial-scale oscillation of temperature may have both wetter and drier periods embedded within them. Consequently, warmth alone is not a sufficient condition for the occurrence of the dryness associated with drought.

Jiang *et al*. (2005) analyzed historical documents to produce a time series of flood and drought occurrences in eastern China's Yangtze Delta since AD 1000. They found alternating wet and dry episodes throughout this lengthy period, and the data demonstrated droughts and floods usually occurred in the spring and autumn seasons of the same year, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850), as opposed to the preceding Medieval Warm Period and the following Current Warm Period.

Zhang *et al*. (2007) developed for China's Yangtze Delta region flood and drought histories of the past thousand years based on "local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." They described this as "a powerful way to characterize the frequency, the intensity, the time position, and the duration of variations in a climate data series." They also compared their results with two 1,000-year temperature histories of the Tibetan Plateau, encompassing northeastern Tibet and southern Tibet.

Zhang *et al*. reported during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they reported during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

Zhang *et al*. (2009) utilized the decadal locust (*Locusta migratoria manilensis*) abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al*. (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al*. (2002) for the AD 950s–1950s to perform a wavelet analysis "to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China." The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events.

The six scientists observed “global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China,” noting these findings “challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects.” They reported their results are an example of “benign effects of global warming on the regional risk of natural disasters.”

Davi *et al*. (2006) employed absolutely dated tree-ring-width chronologies from five sampling sites in the west-central region of Mongolia—all “in or near the Selenge River basin, the largest river in Mongolia”—to develop a reconstruction of streamflow that extended from 1637 to 1997. Of the 10 driest five-year periods of the 360-year record, they found only one occurred during the twentieth century (and that just barely: 1901–1905, sixth driest of the 10 extreme periods), and of the 10 wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the 10 extreme periods, respectively). Consequently, “there is much wider variation in the long-term tree-ring record than in the limited record of measured precipitation,” such that over the course of the twentieth century, which the IPCC describes as having experienced a warming unprecedented over the past one to two millennia, extremes of both dryness and wetness were less frequent and less severe.

Kalugin *et al*. (2005) utilized sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia to produce a multiproxy climate record spanning the past 800 years. This record revealed the regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, however, temperatures cooled and productivity dropped, reaching a broad minimum between 1660 and 1700. This interval “corresponds to the age range of the well-known Maunder Minimum (1645–1715)” and is “in agreement with the timing of the Little Ice Age in Europe (1560–1850).”

With respect to moisture and precipitation, Kalugin *et al.* reported the period between 1210 and 1480 was more humid than today, and the period between 1480 and 1840 was more arid. In addition, they reported three episodes of multiyear drought (1580–1600, 1665–1690, and 1785–1810). These findings are in agreement with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al*., 1996; Panyushkina *et al*., 2000). All of the major multiyear droughts detected in this study occurred during the cool phase of the 800-year record.

Kim *et al*. (2009) developed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006), along with the results of a number of “progressive methods for assessing drought severity from diverse points of view,” including the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), which Kim *et al*. describe as “an intensive measure that considers daily water accumulation with a weighting function for time passage”; a Corrected EDI that “considers the rapid runoff of water resources after heavy rainfall” (CEDI); an Accumulated EDI that “considers the drought severity and duration of individual drought events” (AEDI); and a year-accumulated negative EDI “representing annual drought severity” (YAEDI).

The researchers’ precipitation history and two of their drought severity histories are presented, in that order, in Figures 7.4.2.1 and 7.4.2.2.

The figures clearly show the only major multiyear deviation from long-term normalcy is the decadal-scale decrease in precipitation and ensuing drought, each of which achieved their most extreme values (low in the case of precipitation, high in the case of drought) in the vicinity of AD 1900, well before the twentieth century rise in atmospheric CO_2 and global temperatures. The significant post-Little Ice Age warming of the planet thus had essentially no effect on the long-term histories of either precipitation or drought at Seoul, Korea, adding to the growing body of such findings throughout Asia.

Touchan *et al*. (2003) developed two reconstructions of spring precipitation for south-western Turkey from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia,* and *Pinus nigra*, and the other one (1339–1998) based on three chronologies of *Juniperus excelsa*. The records “show clear evidence of multi-year to decadal variations in spring precipitation.” Nevertheless, the researchers reported “dry periods of 1–2 years were well distributed throughout the record” and the same was largely true of wet periods. With respect to more extreme events, the period preceding the industrial revolution stood out. They note, for example, “all of the wettest 5-year periods occurred prior to 1756.” The longest period of reconstructed spring drought was the four-year period 1476–1479, and the single

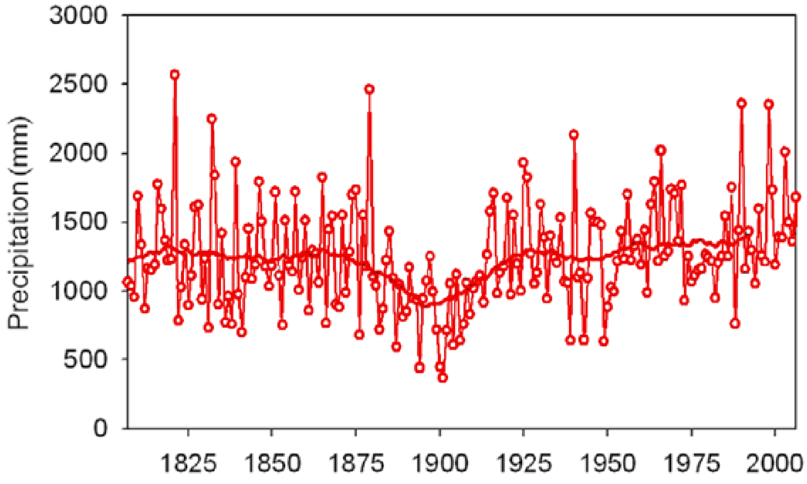

Figure 7.4.2.1. Annual precipitation history at Seoul, Korea, where the solid line represents a 30-year moving-average. Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

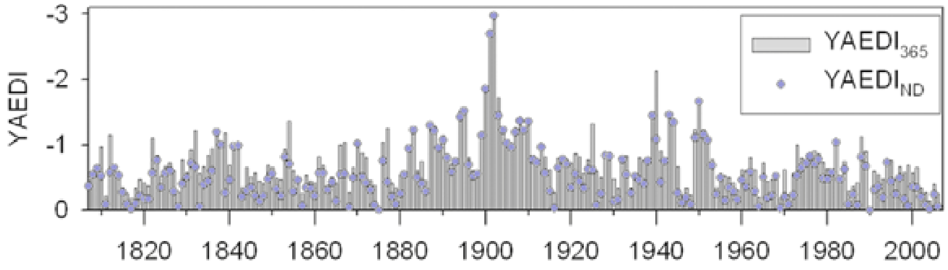

Figure 7.4.2.2. Annual "dryness" history at Seoul, Korea, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12..

driest spring was 1746.

Sinha *et al*. (2007) derived a nearly annually resolved record of Indian summer monsoon (ISM) rainfall variations for the core monsoon region of India from AD 600 to 1500 based on a ^{230}Th-dated stalagmite oxygen isotope record from Dandak Cave, located at 19°00'N, 82°00'E. The authors noted "the short instrumental record of ISM under-estimates the magnitude of monsoon rainfall variability" and "nearly every major famine in India [over the period of their study] coincided with a period of reduced monsoon rainfall as reflected in the Dandak δ^{18}O record." They found two particularly devastating famines "occurred at the beginning of the Little Ice Age during the longest duration and most severe ISM weakening of [their] reconstruction." they also observed "ISM reconstructions from Arabian Sea marine sediments (Agnihotri *et al*., 2002; Gupta *et al*., 2003; von Rad *et al*., 1999), stalagmite δ^{18}O records from Oman and Yemen (Burns *et al*., 2002; Fleitmann *et al*., 2007) and a pollen record from the western Himalaya (Phadtare and Pant, 2006) also indicate a weaker monsoon during the Little Ice Age and a relatively stronger monsoon during the Medieval Warm Period." The eight researchers noted "since the end of the Little Ice Age, ca 1850 AD, the human population in the Indian monsoon region has increased from about 200 million to over 1 billion," and "a recurrence of weaker intervals of ISM comparable to those inferred in our record would have serious implications to human health and economic sustainability in the region."

Sinha *et al*. (2011) warned the return of a severe drought to India could pose a "serious threat for the predominantly agrarian-based societies of monsoon Asia, where the lives of billions of people are tightly intertwined with the annual monsoon cycle." The eight researchers from China, Germany, and the United States reviewed the history of the monsoon, relying heavily on the work of Sinha *et al*. (2007) and Berkelhammer *et al*. (2010).

Sinha *et al*. (2011) observed "proxy reconstructions of precipitation from central India, north-central China [Zhang *et al*., 2008], and southern Vietnam [Buckley *et al*., 2010] reveal a series of monsoon droughts during the mid 14th-15th centuries that each lasted for several years to decades," and "these monsoon megadroughts have no analog during the instrumental period." They noted "emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley *et al*., 2007; Sano *et al*., 2009) and India (Borgaonkar *et al*., 2010) suggest that the mid 14th-15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the Little Ice Age" and "appear to have played a major role in shaping significant regional societal changes at that time." Among these upheavals, they made special mention of "famines and significant political reorganization within India (Dando, 1980; Pant *et al*., 1993; Maharatna, 1996), the collapse of the Yuan dynasty in China (Zhang *et al*., 2008), the Rajarata civilization in Sri Lanka (Indrapala, 1971), and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley *et al*., 2010)," noting the evidence suggests "monsoon megadroughts may have played a major contributing role in shaping these societal changes."

Cluis and Laberge (2001) analyzed streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any changes in Asian river runoff of the type the IPCC predicted would lead to more frequent and more severe drought. They based their study on the streamflow histories of 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region." The mean start and end dates of these series were 1936 ± 5 years and 1988 ± 1 year, respectively, representing an approximate half-century timespan.

With respect to the rivers' annual minimum discharges, which is the measure associated with drought, the authors found 53% were unchanged over the period of the study. Where there were trends, 62% of them were upward, indicative of a growing likelihood of less frequent and less severe drought.

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7.4.3 Europe

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Europe.

Noting "the media often reflect the view that recent severe drought events are signs that the climate has in fact already changed owing to human impacts," Hisdal *et al.* (2001) performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and frequency of drought over the four time periods 1962–1990, 1962–1995, 1930–1995, and 1911–1995. This work revealed "despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied." To the contrary, they found "overall, the number of negative significant trends pointing towards decreasing drought deficit volumes or fewer drought events exceeded the number of positive significant trends (increasing drought deficit volumes or more drought events)."

Linderholm and Chen (2005) derived a 500-year history of winter (September–April) precipitation from tree-ring data obtained within the Northern Boreal zone of Central Scandinavia. This chronology indicated below-average precipitation occurred during the periods 1504–1520, 1562–1625, 1648–1669, 1696–1731, 1852–1871, and 1893–1958, with the lowest values occurring at the beginning of the record and at the beginning of the seventeenth century. For this portion of the European continent, twentieth century global warming did not result in more frequent or more severe droughts.

Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June–August) precipitation in east central Sweden. They found a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record, with the past century exhibiting less variability than the preceding 150 years. A persistent dry episode stood out vividly between 1806 and 1832, when the tree-ring history revealed its longest consecutive period of below-average tree growth, which was associated with a concomitant period of drought documented in the farmer's diary.

Korhonen and Kuusisto (2010) observed "annual mean temperatures in Finland increased by about 0.7°C during the 20th century," citing Jylha *et al.* (2004), while noting under such a warming regime, "both droughts and floods are expected to intensify," a claim made by the IPCC. In a study designed to explore the soundness of this contention, the authors analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland up to the year 2004, using data supplied by the Finnish Environment Institute.

They found as "winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites." They note "the magnitudes of spring high flow have not changed," but low flows "have increased at about half of the unregulated sites due to an increase in both winter and summer discharges." They reported "statistically significant overall changes have not been observed in mean annual discharge."

Here too, Earth did not behave according to the model projections, in this case regarding hydrological responses to global warming. The conflict occurred at both ends of the available moisture spectrum. At the high end, there was no change in the magnitude of flows that can lead to flooding. At the low end, there was an increase in flow magnitude, which either acts to prevent droughts or leads to less frequent and/or less severe episodes of it.

Wilson *et al.* (2005) used the regional curve standardization technique to develop a summer (March–August) precipitation chronology from living and historical ring-widths of trees in the Bavarian Forest region of southeast Germany for the period 1456–2001. This technique captured low frequency variations indicating the region was substantially drier than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870, all intervals much colder than the bulk of the twentieth century.

In the Danube River in western Europe, several researchers studied the precipitation histories of adjacent regions and suggested an anthropogenic signal was present in the latter decades of the twentieth century, attributing that period's supposedly drier conditions to that anthropogenic signal. Ducic

(2005) examined those claims by analyzing observed and reconstructed discharge rates of the river near Orsova, Serbia over the period 1731–1990. Ducic found the lowest 5-year discharge value in the preinstrumental era (1831–1835) was practically equal to the lowest 5-year discharge value in the instrumental era (1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Ducic also reported the discharge rate for the last decade of the record (1981–1990), which prior researchers claimed was anthropogenically influenced, was "completely inside the limits of the whole series" and only 0.7% less than the 260-year mean. The scientist concluded "modern discharge fluctuations do not point to dominant anthropogenic influence." Ducic also concluded the detected cyclicity in the record could "point to the domination of the influence of solar activity."

van der Schrier *et al*. (2006) constructed monthly maps of the Self-Calibrating Palmer Drought Severity Index (SC-PDSI, a variant put forward by Wells *et al*. (2004) of the more common PDSI) for the period 1901–2002 for Europe (35°N–70°N, 10°W–60°E). This index "improves upon the PDSI by maintaining consistent behavior of the index over diverse climatological regions," which "makes spatial comparisons of SC-PDSI values on continental scales more meaningful."

The scientists found "over the region as a whole, the mid-1940s to early 1950s stand out as a persistent and exceptionally dry period, whereas the mid-1910s and late 1970s to early 1980s were very wet." Over the entire study period, they found trends in the continent's summer moisture availability "fail to be statistically significant, both in terms of spatial means of the drought index and in the area affected by drought." In addition, they noted "evidence for widespread and unusual drying in European regions over the last few decades [as suggested by the work of Briffa *et al*. (1994) and Dai *et al*. (2004)] is not supported by the current work," in that "values for the total percentage area subject to extreme moisture conditions in the years 1996–99 returned to normal levels at ~2% from a maximum of nearly 10% in 1990." The four researchers noted "the absence of a trend toward summer desiccation has recently also been observed in soil moisture records in the Ukraine (Robock *et al*., 2005) and supports conclusions in the current study."

Pfister *et al*. (2006) identified extremely low water stages in the Upper Rhine River Basin via hydrological measurements made since 1808 at Basel, Switzerland, while "for the period prior to 1808, rocks emerging in rivers and lakes in the case of low water were used along with narrative evidence for assessing extreme events." This work revealed "29 severe winter droughts are documented since 1540," and these events "occurred after a succession of four months with below-average precipitation" associated with "persistent anticyclones centered over Western Europe." The scientists found "severe winter droughts were relatively rare in the 20th century compared to the former period, which is due to increased winter temperature and precipitation." They noted "extended droughts in the winter half-year in Central Europe were more frequent, more persistent and more severe during the Little Ice Age than in the preceding 'Medieval Warm Period' and the subsequent 'warm 20th century' (Pfister, 2005)."

Renard *et al*. (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high- and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations with a minimum record length of 40 years. These analyses revealed "at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive." At the smaller scale of hydroclimatic regions, they also found no significant results for most regions, although "consistent changes were detected in three geographical areas."

Although small geographical areas often display trends in hydrological regimes of one extreme or the other (high- or low-flow), when scaling up to larger regions such as countries, there is typically less consistent change in extreme behavior. Renard *et al.* concluded "when considered at the global scale," the impact of climate change on hydrological regimes "is still an open question, as illustrated by the lack of a clear signal emerging from large-scale studies (Knudzewicz *et al*., 2005; Svensson *et al*., 2005)."

Buntgen *et al*. (2011) "introduce and analyze 11,873 annually resolved and absolutely dated ring-width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period," and which "allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations." The nine researchers found "a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming." Such findings, Buntgen *et al*. stated, "may question the common belief that frequency and severity of such events closely relates to climate mean states."

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7.4.4 North America

7.4.4.1 Canada

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Canada.

Gan (1998) performed several statistical tests on datasets pertaining to temperature, precipitation, spring snowmelt dates, streamflow, potential and actual evapotranspiration, and the duration, magnitude, and severity of drought throughout the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The results suggested the prairies have become somewhat warmer and drier over the past four to five decades, although there are regional exceptions to this. After weighing the pertinent facts, Gan reported "there is no solid evidence to conclude that climatic warming, if it occurred, has caused the Prairie drought to become more severe." Gan further noted "the evidence is insufficient to conclude that warmer climate will lead to more severe droughts in the Prairies."

Quiring and Papakyriakou (2005) used an agricultural drought index (Palmer's Z-index) to characterize the frequency, severity, and spatial extent of June–July moisture anomalies for 43 crop districts from the agricultural region of the Canadian prairies during 1920–1999. They found the single most severe June–July drought on the Canadian prairies occurred in 1961, and the next most severe droughts, in descending order of severity, occurred in 1988, 1936, 1929, and 1937, showing little net overall trend. The scientists did, however, report an upward trend in mean June–July moisture conditions. In addition, they noted "reconstructed July moisture conditions for the Canadian prairies demonstrate that droughts during the 18th and 19th centuries were more persistent than those of the 20th century (Sauchyn and Skinner, 2001)."

St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak in the Red River basin to reconstruct annual precipitation in southern Manitoba since AD 1409." According to the authors, "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement." The twentieth century warming appears to have induced more stable climatic conditions there, with fewer hydrologic extremes (floods and droughts) than was typical of Little Ice Age conditions. The authors concluded "climatic case studies in regional drought and flood planning based exclusively on experience during the 20th century may dramatically underestimate true worst-case scenarios." They further indicated "multidecadal fluctuations in regional hydroclimate have been remarkably coherent across the northeastern Great Plains during the last 600 years," and "individual dry years in the Red River basin were usually associated with larger scale drought across much of the North American interior," which suggests their results for the Red River basin also likely apply to the entire larger region.

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada to derive a non-vegetation-based high-resolution record of climate variability over the past 4,000 years. Throughout this record, periods of both increasing and decreasing moisture availability, as determined from grain size, were evident at decadal, centennial, and millennial time scales, as also was found by Laird *et al.* (2003) in a study of diatom assemblages in sediment cores taken from three additional Canadian lakes. Over the most recent 150 years, the grain size of the Pine Lake study generally remained above the 4,000-year average, indicative of relatively stable and less droughty conditions than the mean of the past four millennia.

Carcaillet *et al.* (2001) developed high-resolution charcoal histories from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada, after which they determined whether vegetation change or climate change was the primary determinant of the fire frequency variation they observed, comparing their fire history with hydroclimatic reconstructions derived from δ^{18}O and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago when it was significantly warmer than it is today, they found "fire intervals were double those in the last 2000 years," meaning fires were only half as frequent throughout the earlier warmer period as they were during the subsequent cooler era. They also determined "vegetation does not control the long-term fire regime in the boreal forest." Instead, they found "climate appears to be the main process triggering fire." In addition, they reported "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al.*, 1990; Larsen, 1997; Weir *et al.*, 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al.*, 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)."

Girardin *et al.* (2004) developed a 380-year reconstruction of the Canadian Drought Code (CDC), a daily numerical rating of the average moisture content of deep soil organic layers in boreal conifer stands used to monitor forest fire danger, for the month of July based on 16 well-replicated tree-ring chronologies from the Abitibi Plains of eastern Canada just below James Bay. Cross-continuous wavelet transformation analyses of these data "indicated coherency in the 8–16 and 17–32-year per cycle oscillation bands between the CDC reconstruction and the Pacific Decadal Oscillation prior to 1850," whereas "following 1850, the coherency shifted toward the North Atlantic Oscillation."

These results led them to suggest "the end of [the] 'Little Ice Age' over the Abitibi Plains sector corresponded to a decrease in the North Pacific decadal forcing around the 1850s," and "this event could have been followed by an inhibition of the Arctic air outflow and an incursion of more humid air masses from the subtropical Atlantic climate sector," which may have helped reduce fire frequency and drought severity. They noted several other paleoclimate and ecological studies have suggested "climate in eastern Canada started to change with the end of the 'Little Ice Age' (~1850)," citing the works of Tardif and Bergeron (1997, 1999), Bergeron (1998, 2000), and Bergeron *et al.* (2001). Girardin *et al.* further noted Bergeron and Archambault (1993) and Hofgaard *et al.* (1999) have "speculated that the poleward retreat of the Arctic air mass starting at the end of the 'Little Ice Age' contributed to the incursion of moister air masses in eastern Canada."

Wolfe *et al.* (2005) conducted a multiproxy hydroecological analysis of Spruce Island Lake in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta. Their research revealed hydroecological conditions in that region varied substantially during the past 300 years, especially in terms of multidecadal dry and wet periods. Specifically, they found recent drying in the region was not the product of Peace River flow regulation that began in 1968, but rather the product of an extended drying period that was initiated in the early to mid-1900s. They also found the multiproxy hydroecological variables they analyzed were well-correlated with other reconstructed records of natural climate variability and hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with the earlier portion of the record actually depicting "markedly wetter and drier conditions compared to recent decades."

Zhang and Hebda (2005) conducted dendroclimatological analyses of 121 well-preserved subfossil logs discovered at the bottom of Heal Lake near the city of Victoria on Canada's Vancouver Island, plus 29 Douglas-fir trees growing nearby, allowing them to develop an ~4,000-year chronology exhibiting sensitivity to spring precipitation. They found "the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period." As an example, they noted spring droughts represented by ring-width departures exceeding two standard deviations below the mean in at least five consecutive years occurred in the late AD 1840s and mid-1460s, as well as the mid-1860s BC, and were more severe than any drought of the twentieth century. They also found the most persistent drought occurred during the 120-year period between approximately AD 1440 and 1560. Other severe droughts of multidecadal duration occurred in the mid AD 760s–800s, the 540s–560s, the 150s–late-190s, and around 800 BC.

Wavelet analyses of the tree-ring chronology also revealed a host of natural oscillations on timescales of years to centuries, demonstrating the twentieth century was in no way unusual in this regard, as there were many times throughout the prior 4,000 years when it was both wetter and drier than it was during the last century of the past millennium.

Bonsal and Regier (2007) compared the spatial extent and severity of the 2001–2002 Canadian Prairie drought to previous droughts in this region based on data obtained from 21 reporting stations in southern Alberta, Saskatchewan, and Manitoba. They did this for the 1915–2002 period of reasonably extensive instrumental records, using two different drought indicators: the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) at several temporal scales. The two researchers determined "over the agricultural region of the Prairies, 2001 and 2002 generally ranked high in terms of spatial extent and severity of drought," and "at some stations the 2001/2002 drought was the most severe one on record." However, they stated "the SPI and PDSI as drought indicators revealed that the worst and most prolonged Prairie-wide droughts during the instrumental record (1915–2002) ... occurred in the early part of the 20th century (1915 through the 1930s)."

Laird and Cumming (2009) developed a history of changes in the level of Lake 259 (Rawson Lake, 49°40'N, 93°44'W) within the Experimental Lakes Area of northwestern Ontario, Canada, based on a suite of near-shore gravity cores they analyzed for diatom species identity and concentration as well as organic matter content. They found "a distinct decline in lake level of ~2.5 to 3.0 m from ~800 to 1130 AD." This interval "corresponds to an epic drought recorded in many regions of North America from ~800 to 1400 AD," which "is often referred to as the

Medieval Climatic Anomaly or the Medieval Warm Period, and encompasses ‘The Great Drought’ of the thirteenth century (Woodhouse and Overpeck, 1998; Woodhouse, 2004; Herweijer *et al*. 2007).”

The authors also noted the Canadian prairies are currently “experiencing reductions in surface-water availability due to climate warming and human withdrawals (Schindler and Donahue, 2006),” and “many regions in the western U.S. have experienced water supply deficits in reservoir storage with the recent multi-year drought (Cook *et al*., 2007).” They reported “these severe multi-year drought conditions pale in comparison to the many widespread megadroughts that persisted for decades and sometimes centuries in many parts of North America over the last millennium (Woodhouse, 2004).”

Wolfe *et al*. (2011) noted the level of Canada’s Lake Athabasca—North America’s ninth-largest lake, located in the northwest corner of Saskatchewan and the northeast corner of Alberta between 58° and 60° N—“is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains (Wolfe *et al*., 2008; Johnston *et al*., 2010; Sinnatamby *et al*., 2010)” and “paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks (Wolfe *et al*., 2008).” In addition, they reported “the highest levels of the last 1000 years occurred c. 1600–1900 CE [=AD] during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies,” and at the other end of the spectrum they reported the “lowest levels existed at c. 970–1080 CE at a time of low glacier volume,” near the midpoint of the global Medieval Warm Period.

In their newest study of the subject, the four Canadian researchers expanded the timespan of the lake-level history to the past 5,200 years, based on new analyses of sediment cores they collected in July 2004 from North Pond (a lagoon on Bustard Island located at the western end of Lake Athabasca). They discovered “modern society in western Canada developed during a rare interval of relatively abundant freshwater supply—now a rapidly diminishing by-product of the LIA glacier expansion, which is in agreement with late 20th century decline in Athabasca River discharge identified in hydrometric records (Burn *et al*., 2004; Schindler and Donahue, 2006)” (see Figure 7.4.4.1.1). Their data suggested “the transition from water abundance to scarcity can occur within a human lifespan,” which, as they caution, “is a very short amount of time for societies to adapt.”

The data depicted in Figure 7.4.4.1.1 also suggest the peak warmth of the Medieval Warm Period—which was unrelated to any change in the atmosphere’s CO_2 content—was likely significantly greater than the peak warmth to date during the Current Warm Period. The rapidly declining water level during the last couple of decades—when Earth’s temperature was near its modern peak but exhibited very little trend—suggests lake level could continue its rapid downward course if planetary temperatures merely maintain their current values. Therefore, Wolfe *et al*. conclude, “as consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory.”

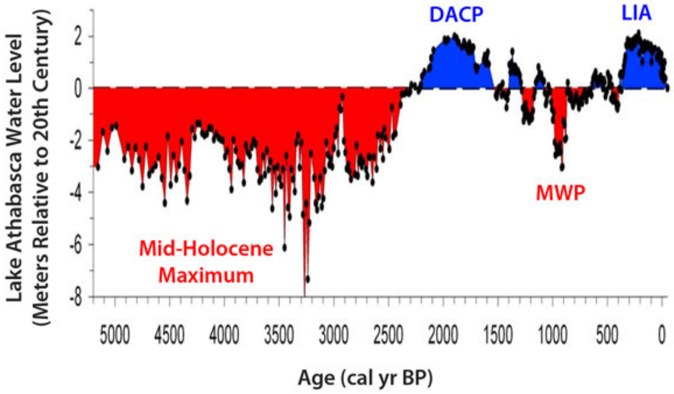

Figure 7.4.4.1.1. The Reconstructed water level history of Lake Athabasca. Adapted from Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.

Sauchyn *et al*. (2011) observed “a growing demand for the surface water resources of the Canadian Prairie Provinces has resulted in increasing vulnerability to hydrological drought,” citing the studies of Schindler and Donahue (2006) and Wheaton *et al*. (2008). They further noted “a shift in the amount and timing of streamflow represents the most serious risk from recent and projected climate warming in western Canada (Sauchyn *et al*., 2010)" and "the Saskatchewan River Basin is among Canada's most vulnerable watersheds, in terms of projected climate changes and impacts, and the sensitivity of natural systems and economic activities to Canada's most variable hydroclimate." It is, of course, important to know the characteristics of past streamflow variability in order to better prepare for future droughts and to determine whether extreme droughts that may occur in the future might be due to CO_2-induced global warming or are within the range of natural variability experienced in the past, when the air's CO_2 concentration was both much lower and less variable than it is currently. Is a mere century of real-world data sufficient for these purposes?

In a study designed to explore this question by determining whether streamflow variability recorded by the streamflow gauge at Edmonton, Alberta (Canada) during the past century (since 1912) is representative of the range of variability experienced there during the past millennium, Sauchyn *et al*. developed a 945-year reconstruction of the annual flow of the Northern Saskatchewan River based on tree rings collected from seven sites within the runoff-generating upper basin of the river (Figure 7.4.4.1.2).

The Edmonton stream-gauge record clearly does not "represent the full extent of interannual to multidecadal variability in the tree-ring data," for as noted by Sauchyn *et al*. "there are periods of low flow in the pre-instrumental record that are longer and more severe than those recorded by the gauge" and which "pre-date Euro-Canadian settlement of the region." Two of these extreme events were droughts of approximately 30 years' duration, one in the early 1700s and another during the mid-1100s. One of the two most prominent megadroughts lasted for most of the fourteenth century, while the other occurred in the latter part of the fifteenth century.

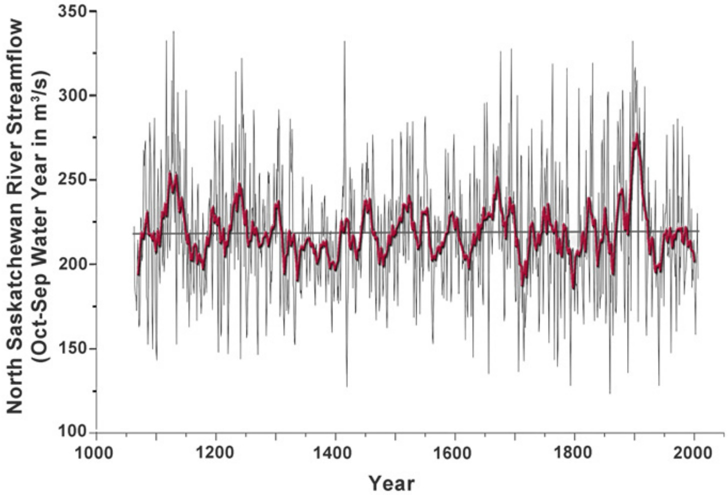

Figure 7.4.4.1.2. North Saskatchewan River reconstructed water year (October to September) flow for the period 1063–2006. Adapted from Sauchyn, D., Vanstone, J., and Perez-Valdivia, C. 2011. Modes and forcing of hydroclimatic variability in the upper North Saskatchewan River Basin since 1063. *Canadian Water Resources Journal* **36**: 205–218.

Sauchyn *et al*. observe "there is less certainty and stationarity in western [Canadian] water supplies than implied by the instrumental record," which is "the conventional basis for water resource management and planning" of the region. Their streamflow reconstruction provides an improved basis for determining the uniqueness of whatever future droughts might occur throughout the region. Their work also makes it more difficult to claim such droughts were caused by anthropogenic CO_2 emissions, since there was far less CO_2 in Earth's atmosphere prior to the 1912 start date of the region's prior streamflow history, when several droughts far more serious than those of the past century occurred.

Laird *et al*. (2012) wrote "future extreme droughts, similar to or more extreme than the 'dust-bowl' 1930s, could be the most pressing problem of global warming," citing Romm (2011) and noting, for comparison, "droughts of unusually long duration" or megadroughts that occurred during the Medieval Climate Anomaly (MCA) "lasted for several decades to centuries thus dwarfing modern-day droughts," as reported by Seager *et al*. (2007) and Cook *et al*. (2010).

Observing "one of the predictions of increasing temperatures is decreased lake levels and river flows (Schindler and Lee, 2010)," the eight researchers stated "analysis of longer-term records of past water levels can provide a context for informing water managers on the inherent natural variability of lake levels and their sensitivity to climate change." They described a pertinent study they conducted on six lakes spread across a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada, where the land-based pollen data of Viau and Gajewski (2009) suggest the presence of warmer temperatures during the MCA.

The diatom-inferred decadal-scale two-millennia-long drought records, which Laird *et* *al*. developed for the six lakes they studied, revealed what they call "periods of synchronous change" had occurred across the six lakes throughout "a period of prolonged aridity during the MCA (c. 900–1400 CE)." They reported this "general synchrony across sites suggests an extrinsic climate forcing (Williams *et al*., 2011)," with the MCA being part of a set of what they call "inherent natural fluctuations."

Laird *et al*. also noted "a widespread external forcing must be large enough for regional patterns to emerge." In the Nebraska Sandhills, they reported, "an analysis of five topographically closed lakes indicated relative coherency over the last 4,000 years, particularly during the MCA with all lakes indicating lake-level decline (Schmieder *et al*., 2011)." In addition, "in Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al*., 2008), high eolian deposition occurred from ~1280 to 1410 CE in Elk Lake (Dean, 1997) and $\delta^{18}O$ from calcite indicated an arid period from ~1100 to 1400 CE in Steel Lake (Tian *et al*., 2006)," while "in Manitoba, the cellulose $\delta^{18}O$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 CE, and a less-severe dry period from 1320 to 1340 CE (Buhay *et al*., 2009)." Relatively warm conditions during the MCA, they added, "have been inferred from pollen records in the central boreal region of Canada and in Wisconsin," citing Viau and Gajewski (2009), Viau *et al*. (2012), and Wahl *et al*. (2012).

These findings have important implications. Most germane to climatology is this: If future extreme droughts, such as those that occurred during the MCA, could indeed be the "most pressing problem" of projected future global warming, as many contend, then it logically follows the Medieval Warm Period must have been far more extreme in terms of high temperature values and their duration than anything yet experienced during the Current Warm Period. That observation is strong evidence that warming considerably in excess of what has been experienced to date in the CWP can occur without any help from rising atmospheric CO_2 concentrations, which were more than 100 ppm less during the Medieval Warm Period than they are today. The great warmth of the MWP is demonstrated by the quantitative and qualitative findings of a host of scientists who have studied the Medieval and Current Warm Periods (see Chapter 4 of this report), all of which further suggests the development of the planet's Current Warm Period may be due to something entirely unrelated to anthropogenic CO_2 emissions.

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7.4.4.2 Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Mexico.

Stahle *et al*. (2000) developed a long-term history of drought over much of North America from reconstructions of the Palmer Drought Severity Index, based on analyses of many lengthy tree-ring records. This history revealed the occurrence of a sixteenth century drought in Mexico that persisted from the 1540s to the 1580s. The authors observed “the ‘megadrought’ of the 16th century far exceeded any drought of the 20th century.”

Diaz *et al*. (2002) constructed a history of winter-spring (November–April) precipitation—which accounts for one-third of the yearly total—for the Mexican state of Chihuahua for the period 1647–1992, based on earlywood width chronologies of more than 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua’s northeast border. They noted “three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century.” Although this observation tends to make the twentieth century look highly anomalous in this regard, it is not; two of those three worst drought years occurred during a period of average to slightly above-average precipitation.

Diaz *et al*. also noted “the longest drought indicated by the smoothed reconstruction lasted 17 years (1948–1964)," again indicative of abnormally dry conditions during the twentieth century. However, for several of the 17 years of that below-normal-precipitation interval, precipitation values were only slightly below normal. Four very similar dry periods were interspersed throughout the preceding two and a half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s.

In the twentieth century, there also was a long period of high winter-spring precipitation from 1905 to 1932, and following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record. With respect to the entire 346 years, Diaz *et al*. found no long-term trend in the data, nor was there evidence of any sustained departure from that trend during the twentieth century, indicating neither twentieth century anthropogenic CO_2 emissions nor twentieth century warming significantly affected rainfall in the Mexican state of Chihuahua.

Cleaveland *et al*. (2003) constructed a winter-spring (November–March) precipitation history for the period 1386–1993 for Durango, Mexico based on earlywood width chronologies of Douglas-fir tree rings collected at two sites in the Sierra Madre Occidental. They reported this record "shows droughts of greater magnitude and longer duration than the worst historical drought that occurred in the 1950s and 1960s." These earlier dramatic droughts included the long dry spell of the 1850s–1860s and what they call the megadrought of the mid- to late-sixteenth century. Their work demonstrates the worst droughts of the past 600 years did not occur during the period of greatest warmth. Instead, they occurred during the Little Ice Age, perhaps the coldest period of the current interglacial.

Hodell *et al*. (2005b) analyzed a 5.1-m sediment core they retrieved from Aguada X'caamal, a small sinkhole lake in northwest Yucatan, Mexico, finding an important hydrologic change occurred there during the fifteenth century AD. The change was documented by the appearance of *A. beccarii* in the sediment profile, a decline in the abundance of charophytes, and an increase in the $\delta^{18}O$ of gastropods and ostracods. In addition, they reported "the salinity and ^{18}O content of the lake water increased as a result of reduced precipitation and/or increased evaporation in the mid- to late 1500s." These changes, as well as many others they cited, were "part of a larger pattern of oceanic and atmospheric change associated with the Little Ice Age that included cooling throughout the subtropical gyre (Lund and Curry, 2004)." They wrote, the "climate became drier on the Yucatan Peninsula in the 15th century AD near the onset of the Little Ice Age," as is also suggested by Maya and Aztec chronicles that "contain references to cold, drought and famine in the period AD 1441–1460."

Hodell *et al*. (1995) provided evidence for a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800–1000), based on their analysis of a sediment core retrieved in 1993 from Lake Chichanacanab in the center of Mexico's northern Yucatan Peninsula. Subsequently, based on two additional sediment cores retrieved from that location in 2000, Hodell *et al*. (2001) determined the massive drought likely occurred in two distinct phases (750–875 and 1000–1075). Reconstructing the climatic history of the region over the past 2,600 years and applying spectral analysis to the data also revealed a significant recurrent drought periodicity of 208 years that matched well with a cosmic ray-produced ^{14}C record preserved in tree rings. This periodicity is believed to reflect variations in solar activity; because of the good correspondence between the two datasets, Hodell *et al.* concluded "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

Hodell *et al*. (2005a) returned to Lake Chichanacanab in March 2004 and retrieved a number of additional sediment cores in some of the deeper parts of the lake. The scientists took multiple cores from the lake's deepest location, from which they obtained depth profiles of bulk density by means of gamma-ray attenuation as well as profiles of reflected red, green, and blue light via a digital color line-scan camera. They observed, "the data reveal in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization." They reported "the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions," and it "included an early phase (ca 770–870) and late phase (ca 920–1100)." They found "the bipartite drought history inferred from Chichancanab is supported by oxygen isotope records from nearby Punta Laguna" and "the general pattern is also consistent with findings from the Cariaco Basin off northern Venezuela (Haug *et al*., 2003), suggesting that the Terminal Classic Drought was a widespread phenomenon and not limited to north-central Yucatan."

Concurrent with the study of Hodell *et al.* (2005a), Almeida-Lenero *et al.* (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala and nearby Lake Quila in the central Mexican highlands approximately 65 km southwest of Mexico City. The scientists determined it was generally more humid than at present in the central Mexican highlands during the mid-Holocene. Thereafter, however, there was a gradual drying of the climate. Their data from Lake Zempoala indicated "the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene." They further noted this interval of 200 years "coincides with the collapse of the Maya civilization." They reported their data from Lake Quila were "indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP." In addition, they noted "climatic aridity during this time was also noted by Metcalfe *et al.* (1991) for the Lerma Basin [central Mexico]" and "dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982)." The "dry conditions were also reported for [Mexico's] Zacapu Basin (Metcalfe, 1995) and for [Mexico's] Yucatan Peninsula (Curtis *et al.*, 1996, 1998; Hodell *et al.*, 1995, 2001)."

Therrell *et al.* (2006) "developed a continuous, exactly dated, tree-ring reconstruction of maize yield variability" over the period 1474 to 2001 in an effort to provide "new insight into the history of climate and food availability in the heartland of the Mesoamerican cultural province." They relied on latewood-width data derived from "the second-most southerly native stand of Douglas-fir (*Pseudtosuga menziesii*) trees known in the Americas" and compared their reconstruction to "historical records of crop failure and famine in order to cross-validate the tree-ring and historical records."

Therrell *et al.*'s plot of reconstructed drought-induced maize-yield anomalies exposed seven major decadal-scale yield shortfalls over the past 500 years, with a mean rate of occurrence of 1.5 per century over the 400-year period AD 1500–1900. In the twentieth century, there was only one such multiyear famine, and its magnitude paled in comparison to that of the average such event of the preceding four centuries.

Metcalfe and Davies (2007) synthesized the findings of a variety of paleoclimate studies based on analyses of the sediment records of several crater lakes and lakes formed by lava dams scattered across the Trans Mexican Volcanic Belt of central Mexico with an absolute chronology provided by radiocarbon dates extending back to 1500 ^{14}C yr BP. Noting the degree of coherence among the records "is remarkable," Metcalf and Davis reported "dry conditions, probably the driest of the Holocene, are recorded over the period 1400 to 800 ^{14}C yr BP (ca. AD 700–1200)." The authors reported the results were "consistent with results from the Yucatan Peninsula (Hodell *et al*., 1995, 2005) ... and from the Cariaco basin (Haug *et al*., 2003) and the Isthmus of Panama (Lachniet *et al*., 2004)."

Dominguez-Vazquez and Islebe (2008) derived a 2,000-year history of regional drought for the Lacandon Forest Region in the state of Chiapas, southeastern Mexico. Based on radiocarbon dating and pollen analyses of a sediment core retrieved from the shore of Naja Lake (16°59'27.6"N, 91°35'29.6"W), the two authors reported "a marked increase in *Pinus* pollen, together with a reduction in lower montane rain forest taxa, [which they] interpreted as evidence for a strong, protracted drought from 1260 to 730 years BP," which they characterized as "the most severe" while noting it "coincides with the Maya classic collapse."

Escobar *et al.* (2010) examined sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula as a proxy measure for high-frequency climate variability. The five researchers found "relatively dry periods were persistently dry, whereas relatively wet periods were composed of wet and dry times." They noted their findings "confirm the interpretations of Hodell *et al.* (1995, 2007) and Curtis *et al.* (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period." They found "the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the last 3,000 years, but also a persistently dry period." In further support of this interpretation, they note "the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability."

Figueroa-Rangel *et al.* (2010) used fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35'32"N, 104°16'56"W) to construct a 1,300-year history of cloud forest vegetation dynamics in the Sierra de Manantlan Biosphere Reserve (SMBR, in west-central Mexico). The authors found "during intervals of aridity, cloud forest taxa tend to become reduced," whereas "during intervals of increased humidity, the cloud forest thrives." They determined there was a major dry period from approximately AD 800 to 1200 in the SMBR and observed "results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region (B.L. Figueroa-Rangel, unpublished data); in central Mexico (Metcalf and Hales, 1994; Metcalfe, 1995; Arnauld *et al*., 1997; O'Hara and Metcalfe, 1997; Almeida-Lenero *et al*., 2005; Ludlow-Wiechers *et al*., 2005; Metcalfe *et al*., 2007); lowlands of the Yucatan Peninsula (Hodell *et al*., 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug *et al*., 2003)." In addition, they reported "the causes associated to this phase of climate change have been attributed to solar activity (Hodell *et al*., 2001; Haug *et al*., 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe *et al*., 2000; Hodell *et al*., 2005a,b; Berrio *et al*., 2006) and to ENSO variability (Metcalfe, 2006)."

Throughout much of Mexico, some of the driest conditions and worst droughts of the Late Holocene occurred prior to the late twentieth and early twenty-first centuries. These observations contradict assertions that global warming will cause drought conditions to worsen, especially considering the Mexican droughts of the twentieth century and early twenty-first century were much milder than many of that occurred during the much colder centuries of the Little Ice Age and the warmer Medieval Warm Period. The latter observation suggests that to attribute warmth as the cause of droughts means acknowledging the Medieval Warm Period extended beyond the North Atlantic and was significantly warmer than current and recent temperatures.

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7.4.4.3 United States

7.4.4.3.1 Central

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the central United States.

The United States' Northern Great Plains is an important agricultural region of North America, providing a significant source of grain both locally and internationally. It is susceptible to extreme droughts that tend to persist longer than in any other region of the country (Karl *et al*., 1987; Soule, 1992), making it a good place to review the history of drought to determine whether the region is currently experiencing a manifestation of the model-based claim (Gore, 2006; Mann and Kump, 2008) that global warming will usher in a period of more frequent and intense drought.

Mauget (2004) looked for what he called "initial clues" to the commencement of the great drying of the U.S. heartland predicted to occur in response to CO_2-induced global warming by Manabe and Wetherald (1987), Rind *et al*. (1990), Rosenzweig and Hillel (1993), and Manabe *et al*. (2004), which Mauget reasoned would be apparent in the observational streamflow record of the region. He employed data obtained from the archives of the U.S. Geological Survey's Hydro-Climatic Data Network, 42 stations covering the central third of the United States stretching from the Canadian border on the north to the Gulf of Mexico on the south, with the densest coverage existing within the U.S. corn belt.

Mauget found "an overall pattern of low flow periods before 1972, and high flow periods occurring over time windows beginning after 1969." Of the 42 stations' high flow periods, he observed "34 occur during 1969–1998, with 25 of those periods ending in either 1997 or 1998," and "of those 25 stations 21 are situated in the key agricultural region known as the Corn Belt." He also found "among most of the stations in the western portions of the Corn Belt during the 1980s and 1990s there is an unprecedented tendency toward extended periods of daily high flow conditions, which lead to marked increases in the mean annual frequency of hydrological surplus conditions relative to previous years." Furthermore, he found "in 15 of the 18 Corn Belt gage stations considered here at daily resolution, a more than 50% reduction in the mean annual incidence of hydrological drought conditions is evident during those periods." Finally, Mauget reported "the gage station associated with the largest watershed area—the Mississippi at Vicksburg—shows more than a doubling of the mean annual frequency of hydrological surplus days during its 1973–1998 high flow period relative to previous years, and more than a 50% reduction in the mean annual incidence of hydrological drought condition."

Mauget observed the overall pattern of climate variation "is that of a reduced tendency to hydrological drought and an increased incidence of hydrological surplus over the Corn Belt and most of the Mississippi River basin during the closing decades of the 20th century." He further noted "some of the most striking evidence of a transition to wetter conditions in the streamflow analyses is found among streams and rivers situated along the Corn Belt's climatologically drier western edge."

Do such findings represent the early stages of real-world climate change? Mauget found the streamflow data do indeed "suggest a fundamental climate shift, as the most significant incidence of high ranked annual flow was found over relatively long time scales at the end of the data record." That shift, however, is *away from* more frequent and severe drought.

Shapley *et al*. (2005) undertook a longer-term study of the topic, developing a 1,000-year hydro-climate reconstruction from local bur oak tree-ring records and various lake sediment cores in the Northern Great Plains. Prior to 1800, they determined, "droughts tended towards greater persistence than during the past two centuries," suggesting droughts of the region became shorter-lived as opposed to longer-lasting as Earth gradually recovered from the cold temperatures of the Little Ice Age.

Daniels and Knox (2005) analyzed the alluvial stratigraphic evidence for an episode of major channel incision in tributaries of the upper Republican River occurring between 1100 and 800 years ago, after which they compared their findings with proxy drought records from 28 other locations throughout the Great Plains and surrounding regions. This work revealed channel incision in the Republican River between approximately AD 900 and 1200 was well correlated with a multi-centennial episode of widespread drought, which in the words of Daniels and Knox "coincides with the globally recognized Medieval Warm Period." Modern twentieth century warming has not led to a repeat of those widespread drought conditions.

Stambaugh *et al*. (2011) "used a new long tree-ring chronology developed from the central U.S. to reconstruct annual drought and characterize past drought duration, frequency, and cycles in the agriculturally important U.S. Corn Belt region during the last millennium." They calibrated and verified this chronology against monthly values of the instrumental Palmer Hydrologic Drought Index during the summer season of June, July, and August. The six scientists reported "20th century droughts, including the Dust Bowl, were relatively unremarkable when compared to drought durations prior to the instrumental record." They noted, for example, the nineteenth century was the driest of the past millennium, with major drought periods occurring from about 1816 to 1844 and 1849 to 1880, during what they described as the transition out of the Little Ice Age. Prior to that, there had been 45 years of drought in the latter part of the seventeenth century coincident with the Maunder Minimum of solar activity, which is associated with the coldest period of the current interglacial.

Going back further in time, Stambaugh *et al.* found an approximately 35-year drought in the mid- to late-fifteenth century during "a period of decreased radiative forcing and northern hemisphere temperatures." Eclipsing them all, however, was "the approximately 61-year drought in the late 12th century (ca. AD 1148-1208)," which "appears to be the most significant drought of the entire reconstruction" and in fact "corresponds to the single greatest megadrought in North America during the last 2000 years (Cook *et al*., 2007)," as well as "unmatched persistent low flows in western U.S. river basins (Meko *et al*., 2007)." This drought, the authors reported, occurred during the middle of the Medieval Warm Period—"an interval of warmer temperatures between approximately AD 800–1300 characterized by greater drought duration and frequency in the Northern Great plains compared to more modern times."

Stambaugh *et al.*'s findings show there is nothing unusual, unnatural, or unprecedented about any twentieth or twenty-first century droughts that may have hit the agricultural heartland of the United States. It is also clear the much greater droughts of the past millennium occurred during periods of both relative cold and relative warmth, as well as the transitions between them.

Forman *et al.* (2005) observed "periods of dune reactivation reflect sustained moisture deficits for years to decades and reflect broader environmental change with diminished surface- and ground-water resources," which prompted them to focus on "the largest dune system in North America, the Nebraska Sand Hills." They utilized "recent advances in optically stimulated luminescence dating (Murray and Wintle, 2000) to improve chronologic control on the timing of dune reactivation" while linking landscape response to drought over the past 1,500 years to tree-ring records of aridity.

Forman *et al.* identified six major aeolian depositional events in the past 1,500 years, all but one of which (the 1930s "Dust Bowl" drought) occurred prior to the twentieth century. Moving back in time from the Dust Bowl, the preceding three major events occurred during the depths of the Little Ice Age, near the Little Ice Age's inception, and near the end of the Dark Ages Cold Period. As for how the earlier droughts compared with those of the past century, the researchers found the 1930s drought (the twentieth century's worst depositional event) was less severe than the others, especially the sixteenth century megadrought. Forman *et al.* concluded the aeolian landforms "are clear indicators of climate variability beyond twentieth century norms, and signify droughts of greater severity and persistence than thus far instrumentally recorded." Their study also reveals post-Little Ice Age warming—which is often claimed to be unprecedented over the past two millennia—has not produced similarly unprecedented droughts.

Advancing the field of study back further in time, Woodhouse and Overpeck (1998) reviewed what is known about the frequency and severity of drought in the central United States over the past 2,000 years based upon empirical evidence of drought from various proxy indicators. Their study indicated the presence of numerous "multidecadal- to century-scale droughts," leading them to conclude "twentieth-century droughts are not representative of the full range of drought variability that has occurred over the last 2000 years." In addition, they observed the twentieth century was characterized by droughts of "moderate severity and comparatively short duration, relative to the full range of past drought variability."

With respect to the causes of drought, Woodhouse and Overpeck suggested there might be several either directly or indirectly inducing changes in atmospheric circulation and moisture transport. They cautioned "the causes of droughts with durations of years (i.e., the 1930s) to decades or centuries (i.e., paleodroughts) are not well understood." Hence, they concluded, "the full range of past natural drought variability, deduced from a comprehensive review of the paleoclimatic literature, suggests that droughts more severe than those of the 1930s and 1950s are likely to occur in the future." This is likely to be the case irrespective of future atmospheric CO_2 concentrations or temperatures.

Fritz *et al.* (2000) constructed three 2,000-year histories of lake-water salinity at three sites in North Dakota—Moon Lake, Coldwater Lake, and Rice Lake—to infer regional patterns of drought and comment on its potential cause. "From the vantage point of the 20th century," they observed, "the three North Dakota sites suggest that droughts equal or greater in magnitude to those of the Dust Bowl period were a common occurrence during the last 2000 years and that severe droughts may have been frequent for multiple decades within this period." In addition, they reported "studies from the northern Great Plains and western North America (Cook *et al.*, 1997; Dean, 1997; Laird *et al.*, 1996; Yu and Ito, 1999) have shown a correlation between solar forcing and centennial- and decadal-scale drought patterns." They conclude "solar variability may influence the duration of dry periods through its impact on convective activity and circulation (Rind and Overpeck, 1993)."

Laird *et al.* (1998) examined the region's historical record of drought in an attempt to establish a baseline of natural drought variability that could help in attempts to determine whether current and future droughts might be anthropogenically influenced. Working with a high-resolution sediment core obtained from Moon Lake, North Dakota, which provided a subdecadal record of salinity (drought) over the past 2,300 years, they discovered the U.S. Northern Great Plains were relatively wet during the final 750 years of this period. Throughout the 1,550 prior years, Laird *et al*. found "recurring severe droughts were more the norm" and were "of much greater intensity and duration than any in the 20th century," including the great Dust Bowl event of the 1930s. Consequently, and in light of their finding "no modern equivalents" to Northern Great Plains droughts experienced prior to AD 1200, it would appear twentieth century global warming has had no effect on drought conditions in this part of the world.

Tian *et al*. (2006) derived a 31-century high-resolution $\delta^{18}O$ record of aridity from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. Among their findings, they noted "the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods." Most striking, they found "drought variability was anomalously low during the 20th century"—so depressed that "~90% of the variability values during the last 3100 years were greater than the 20th-century average."

The above findings show there is nothing unusual, unnatural, or unprecedented about recent droughts in the Central United States. Droughts of greater duration and intensity have occurred numerous times in the past. Claims of increasing future drought as a result of global warming are not supported by real-world data, as modern global warming has, if anything, tended to lessen drought conditions throughout the central United States.

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7.4.4.3.2 Eastern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the eastern United States.

Pederson *et al*. (2012) note drought is "a pervasive phenomenon throughout much of North America with profound ecological and societal implications," as has been suggested by the work of Hursh and Haasis (1931), Breshears *et al*. (2005), Manuel (2008), and Allen *et al*. (2010). Citing Knight (2004) and Seager *et al*. (2009), they report recent moisture deficits in the southeastern United States have renewed water management challenges that underscore the need to "better understand drought processes in humid, subtropical regions." Pederson *et al*. attempted "to put the region's recent drought variability in a long-term perspective" by reconstructing historic drought trends in the Apalachicola-Chattahoochee-Flint river basin over the period 1665–2010 using a dense and diverse tree-ring network. This network, they wrote, "accounts for up to 58.1% of the annual variance in warm-season drought during the 20th century and captures wet eras during the middle to late 20th century."

The 12 researchers found the Palmer Drought Severity Index reconstruction for their study region revealed "recent droughts are not unprecedented over the last 346 years" and "droughts of extended duration occurred more frequently between 1696 and 1820," when most of the world was in the midst of the Little Ice Age. They also found their results "confirm the findings of the first reconstruction of drought in the southern Appalachian Mountain region, which indicates that the mid-18th and early 20th centuries were the driest eras since 1700," citing Stahle *et al*. (1988), Cook *et al*. (1998), and Seager *et al*. (2009).

Quiring (2004) introduced his study of the subject by describing the drought of 2001–2002, which by June of the latter year produced anomalously dry conditions along most of the east coast of the country, including severe drought conditions from New Jersey to northern Florida forcing 13 states to ration water. Shortly after the drought began to subside in October 2002, however, moist conditions returned and persisted for about a year, producing the wettest growing-season of the instrumental record. These observations, in Quiring's words, "raise some interesting questions," including, "are moisture conditions in this region becoming more variable?"

Using an 800-year tree-ring-based reconstruction of the Palmer Hydrological Drought Index, Quiring documented the frequency, severity, and duration of growing-season moisture anomalies in the southern mid-Atlantic region of the United States. Among other things, this work revealed "conditions during the 18th century were much wetter than they are today, and the droughts that occurred during the 16th century tended to be both longer and more severe." He concluded "the recent growing-season moisture anomalies that occurred during 2002 and 2003 can only be considered rare events if they are evaluated with respect to the relatively short instrumental record (1895–2003).” When compared to the 800-year reconstructed record, he observed, “neither of these events is particularly unusual.” In addition, Quiring reported, “although climate models predict decreases in summer precipitation and significant increases in the frequency and duration of extreme droughts, the data indicate that growing-season moisture conditions during the 20th century (and even the last 19 years) appear to be near normal (well within the range of natural climate variability) when compared to the 800-year record.”

Cronin *et al.* (2000) studied the salinity gradient across sediment cores from Chesapeake Bay, the largest estuary in the United Sates, in an effort to examine precipitation variability in the surrounding watershed during the past millennium. Their work revealed the existence of a high degree of decadal and multidecadal variability between wet and dry conditions throughout the 1,000-year record, when regional precipitation totals fluctuated by 25 to 30%, often in “extremely rapid [shifts] occurring over about a decade.” In addition, precipitation over the last two centuries of the record was generally greater than it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the local climate was found to be “extremely wet.” The 10 researchers also found the region experienced several “megadroughts” that lasted for 60 to 70 years, several of which were “more severe than twentieth century droughts.”

Willard et al. (2003) built upon the work of Cronin *et al.*, examining the last 2,300 years of the Holocene record for Chesapeake Bay and the adjacent terrestrial ecosystem “through the study of fossil dinoflagellate cysts and pollen from sediment cores.” They found “several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records.” The first of these periods of lower-than-average precipitation (200 BC–AD 300) occurred during the latter part of the Roman Warm Period, and the next such period (~AD 800–1200) “corresponds to the ‘Medieval Warm Period.’” In addition, they identified several decadal-scale dry intervals spanning the years AD 1320–1400 and 1525–1650.

Willard *et al.* noted “mid-Atlantic dry periods generally correspond to central and southwestern USA ‘megadroughts’, which are described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity.” They observed “droughts in the late sixteenth century that lasted several decades, and those in the ‘Medieval Warm Period’ and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al.*, 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al.*, 2000; Laird *et al.*, 1996a, 1996b) and detrital clastic records (Dean, 1997).” Their work in the eastern United States, together with the work of researchers in other parts of the country, demonstrates twentieth-century global warming has not led to the occurrence of unusually strong wet or dry periods.

Springer *et al.* (2008) constructed a multidecadal-scale history of east-central North America’s hydroclimate covering the past 7,000 years, based on Sr/Ca ratios and $\delta^{13}C$ data obtained from stalagmite BCC-002 of Buckeye Creek Cave (BCC) in West Virginia, USA. The authors detected seven significant mid- to late-Holocene droughts that “correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle,” as per Bond *et al.* (1997, 2001). In addition, they found “the Sr/Ca and $\delta^{13}C$ time series display periodicities of ~200 and ~500 years,” “the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle,” and the ~500-year periodicity is likely “a harmonic of the IRD oscillations.” They also reported “cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years,” and these latter values “are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity.” Such findings “corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau *et al.*, 2002; Willard *et al.*, 2005; Denniston *et al.*, 2007).” Their high-resolution time series also “provide much stronger evidence in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results.”

Palaeoclimate data from the eastern United States, as highlighted in this section, show droughts are not becoming more extreme and erratic in response to global warming.

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7.4.4.3.3 Western

7.4.4.3.3.1 Pacific Northwest

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Pacific Northwest region of the United States.

Knapp *et al*. (2002) created a 500-year history of severe single-year Pacific Northwest droughts from a study of 18 western juniper tree-ring chronologies identifying what they call extreme Climatic Pointer Years, or CPYs, indicative of severe single-year droughts. This procedure revealed “widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries,” and “both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread.” Thereafter, however, “CPYs became more numerous during the 20th century,” although the number of twentieth century extreme CPYs (26) was still substantially less than the mean of sixteenth and seventeenth century extreme CPYs (38), when the planet was considerably colder.

Gedalof *et al*. (2004) used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water-year flow since 1750 on the Columbia River at The Dales in Oregon. They conducted this study of the second largest drainage basin in the United States “for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events.” The study revealed “persistent low flows during the 1840s were probably the most severe of the past 250 years” and “the drought of the 1930s is probably the second most severe.”

More recent droughts, in the words of the researchers, “have led to conflicts among uses (e.g., hydroelectric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of access to water (in particular junior water rights holders in the agricultural sector).” Nevertheless, they observed, “these recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events.” They also found “the period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events,” demonstrating Pacific Northwest droughts have not become more severe or long-lasting as temperatures rose during the twentieth century.

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7.4.4.3.3.2 Idaho/Montana/Wyoming

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Idaho, Montana, and Wyoming in the United States.

Wise (2010) noted “the 1667 km Snake River is one of the largest rivers in the United States, draining a semiarid region that covers 283,000 km^2 [and] includes most of Idaho, as well as portions of Wyoming, Utah, Nevada, Oregon, and Washington.” She observed the river’s water has been “historically allocated almost entirely for agricultural irrigation” and the Snake River is “the largest tributary of the Columbia River (based on both discharge and watershed size),” which makes it “also important for users further downstream.” Wise reported “the 20th century was an abnormally wet period in this region (Gray and McCabe, 2010),” but an early twenty-first century drought “has raised questions about whether these dry conditions should be considered an extreme event or if this drought is within the range of natural variability.”

Wise utilized tree-ring samples collected near the headwaters of the Snake River in Wyoming augmented with preexisting tree ring chronologies to extend the short (1911–2006) instrumental water supply record of the region. This provided the first multi-century (1591–2005) record of the river's water supply variability, which could then provide context for the early twenty-first century drought in this region. She found "individual low-flow years in 1977 and 2001 and the longer-term 1930s Dust Bowl drought meet or exceed the magnitude of dry periods in the extended reconstructed period." In terms of overall severity, "the instrumental record does not contain a drought of the extent seen in the mid-1600s." Wise further observed "twenty-four of 34 years in the 1626–1659 time period had below-average flow, including periods of six and seven consecutive below-mean years (1626–1632 and 1642–1647)," and "during the most severe period from 1626 to 1647, 17 of 22 years (77%) were below-normal flow." She concluded "this type of event could represent a new 'worst-case scenario' for water planning in the upper Snake River."

Gray *et al.* (2004) used cores and cross sections from 79 Douglas fir and limber pine trees at four sites in the Bighorn Basin of north-central Wyoming and south-central Montana to develop a proxy for annual precipitation spanning the period AD 1260–1998. This reconstruction, in their words, "exhibits considerable nonstationarity, and the instrumental era (post-1900) in particular fails to capture the full range of precipitation variability experienced in the past ~750 years." They found "both single-year and decadal-scale dry events were more severe before 1900" and "dry spells in the late thirteenth and sixteenth centuries surpass both [the] magnitude and duration of any droughts in the Bighorn Basin after 1900." They observed "single- and multi-year droughts regularly surpassed the severity and magnitude of the 'worst-case scenarios' presented by the 1930s and 1950s droughts."

In a study covering a much longer period of time, Persico and Meyer (2009) studied "beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park." They compared "the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region," finding "gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP are contemporaneous with increased charcoal accumulation rates in Yellowstone lakes and peaks in fire-related debris-flow activity, inferred to reflect severe drought and warmer temperatures (Meyer *et al.*, 1995)." In addition, they noted "the lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly, a time of widespread multi-decadal droughts and high climatic variability in Yellowstone National Park (Meyer *et al.*, 1995) and the western USA (Cook *et al.*, 2004; Stine, 1998; Whitlock *et al.*, 2003)." The lack of evidence for beaver activity 2200–1800 cal yr BP is concurrent with the Roman Warm Period. In both of these periods, the researchers concluded, the severe droughts "likely caused low to ephemeral discharges in smaller streams, as in modern severe drought," implying the Medieval and Roman Warm Periods were likely just as dry and warm as it is today.

These findings suggest there is nothing unusual, unnatural, or unprecedented about the degree of warmth and drought in the Current Warm Period. The regular recurrence of such drought conditions suggests their cause is a cyclical phenomenon of nature independent of the activities of the planet's human population.

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7.4.4.3.3.3 Nevada/Utah

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Nevada and Utah in the United States.

Benson *et al*. (2002) developed continuous high-resolution $\delta^{18}O$ records from cored sediments of Pyramid Lake, Nevada, which they used to help construct a 7,600-year history of droughts throughout the surrounding region. Oscillations in the hydrologic balance evident in this record occurred, on average, about every 150 years, but with significant variability. Over the most recent 2,740 years, for example, intervals between droughts ranged from 80 to 230 years, and drought durations ranged from 20 to 100 years. Some of the larger droughts forced mass migrations of indigenous peoples from lands that could no longer support them. In contrast, droughts of the historical instrumental record typically have lasted less than a decade.

Mensing *et al*. (2004) analyzed sediment cores for pollen and algal microfossils deposited at Pyramid Lake, Nevada during the prior 7,630 years, which allowed them to infer the hydrologic history of the area over that period. They found "sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet," but "the past 2500 yr have been marked by recurring persistent droughts." The longest of these droughts "occurred between 2500 and 2000 cal yr B.P.," and others occurred "between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P," with none recorded in more recent, warmer times.

The researchers also noted "the timing and magnitude of droughts identified in the pollen record compare favorably with previously published $\delta^{18}O$ data from Pyramid Lake" and with "the ages of submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada." Finally, noting Bond *et al*. (2001) "found that over the past 12,000 yr, decreases in [North Atlantic] drift ice abundance corresponded to increased solar output," they reported when they "compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice ... nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record." Mensing *et al*. concluded "changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States]."

Gray *et al*. (2004) used samples from 107 piñon pines at four sites in Utah to develop a proxy record of annual precipitation spanning the AD 1226–2001 interval for the Uinta Basin watershed in the northeastern portion of the state. This revealed "single-year dry events before the instrumental period tended to be more severe than those after 1900" and decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found "dry events in the late 13th, 16th, and 18th Centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900."

Considering the other end of the moisture spectrum, Gray *et al*. reported the twentieth century was host to two of the strongest wet intervals (1938–1952 and 1965–1987), although these periods were only the seventh and second most intense wet regimes, respectively, of the entire record. It would appear precipitation extremes (both high and low) in northeastern Utah's Uinta Basin have become more attenuated as opposed to more amplified in conjunction with twentieth-century global warming.

MacDonald and Tingstad (2007) examined instrumental climate records to outline historical spatiotemporal patterns of precipitation variability in the Uinta Mountains, after which they "used tree-ring width chronologies from *Pinus edulis* Engelm (two-needle pinyon pine) trees growing near the northern and southern flanks of the mountains to produce an ~600-year reconstruction (AD 1405–2001) of Palmer Drought Severity Index [PDSI] for Utah Climate Division 5," which they say "allows for the placement of 20th century droughts within the longer context of natural drought variability and also allows for the detection of long-term trends in drought."

MacDonald and Tingstad reported "in the context of prolonged severe droughts," the twentieth century "has been relatively moist compared to preceding centuries." The scientists reported their PDSI reconstruction and the Uinta Basin precipitation reconstruction indicate "the early to mid 17th century in particular, and portions of the 18th and 19th centuries, experienced prolonged (>10 years) dry conditions that would be unusually severe by 20th century standards." They noted "the most striking example of widespread extended drought occurred during a ~45-year period between 1625 and 1670 when PDSI only rarely rose above negative values."

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7.4.4.3.3.4 California

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to California in the United States.

Malamud-Roam *et al.* (2006) conducted an extensive review of "the variety of paleoclimatic resources for the San Francisco Bay and watershed in order to identify major climate variations in the pre-industrial past, and to compare the records from the larger watershed region with the Bay records in order to determine the linkages between climate experienced over the larger watershed region and conditions in the San Francisco Bay." They found "intermittent mega-droughts of the Medieval Climate Anomaly (ca. AD 900–1350) coincided with a period of anomalously warm coastal ocean temperatures in the California Current," and "oxygen isotope compositions of mussel shells from archaeological sites along the central coast also indicate that sea surface temperatures were slightly warmer than present." In contrast, they noted "the Little Ice Age (ca. AD 1450–1800) brought unusually cool and wet conditions to much of the watershed," and "notably stable conditions have prevailed over the instrumental period, i.e., after ca. AD 1850, even including the severe, short-term anomalies experienced during this period," namely, "the severe droughts of the 1930s and the mid-1970s." When longer paleoclimate records are considered, they noted, "current drought conditions experienced in the US Southwest do not appear out of the range of natural variability." However, they speculated, "warmer temperatures associated with anthropogenic global warming may exacerbate such conditions," which would suggest current temperatures are not as warm as during the Medieval Warm Period.

In a study of "perfect drought" in Southern California (USA), MacDonald *et al.* (2008) defined the term as "a prolonged drought that affects southern California, the Sacramento River basin and the upper Colorado River basin simultaneously." They noted the instrumental record indicates the occurrence of such droughts throughout the past century, but they "generally persist for less than five years." That they have occurred at all, however, suggests the possibility of even longer perfect droughts, which could prove catastrophic for the region.

The three researchers explored the likelihood of such droughts occurring in the future based on dendrochronological reconstructions of the winter Palmer Drought Severity Index (PDSI) in southern California over the past thousand years, plus the concomitant annual discharges of the Sacramento and Colorado Rivers, under the logical assumption that what has occurred before may occur again. MacDonald *et al.* reported finding "prolonged perfect droughts (~30-60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th century during the period of the so-called 'Medieval Climate Anomaly.'" This led them to conclude "prolonged perfect droughts due to natural or anthropogenic changes in radiative forcing, are a clear possibility for the near future."

Kleppe *et al.* (2011) reconstructed the duration and magnitude of extreme droughts in the northern Sierra Nevada region based on dendrochronology, geomorphic analysis, and hydrologic modeling of the Fallen Leaf Lake (California) watershed in order to estimate paleo-precipitation near the headwaters of the Truckee River-Pyramid Lake watershed of eastern California and northwestern Nevada. The six scientists found "submerged Medieval trees and geomorphic evidence for lower shoreline corroborate a prolonged Medieval drought near the headwaters of the Truckee River-Pyramid Lake watershed," and water-balance calculations independently indicated precipitation was "less than 60% normal." They noted these findings "demonstrate how prolonged changes of Fallen Leaf's shoreline allowed the growth and preservation of Medieval trees far below the modern shoreline." In addition, they noted age groupings of such trees suggest similar megadroughts "occurred every 600–1050 years during the late Holocene."

The findings of Kleppe *et al.*, and many others whose works they cite, suggest the Medieval Warm Period experienced substantially less precipitation and far longer and more severe drought than what has been experienced to date in the Current Warm Period. In addition, their data suggest such dry conditions have occurred regularly, in cyclical fashion, "every 650–1150 years during the mid- and late-Holocene." These observations suggest there is nothing unusual, unnatural, or unprecedented about the nature of drought during the Current Warm Period in the western United States.

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7.4.4.3.3.5 Colorado/Colorado River Basin

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Colorado and the Colorado River Basin of the United States.

Hidalgo *et al.* (2000) used a new form of principal components analysis to reconstruct a history of streamflow for the Upper Colorado River Basin based on information obtained from tree-ring data, after which they compared their results to those of Stockton and Jacoby (1976). They found the two approaches yielded similar results, except Hidalgo *et al.*'s approach responded with more intensity to periods of below-average streamflow or regional drought. Thus it was easier for them to determine there has been "a near-centennial return period of extreme drought events in this region," going back to the early 1500s.

Woodhouse *et al.* (2006) also generated proxy reconstructions of water-year streamflow for the Upper Colorado River Basin, based on four key gauges (Green River at Green River, Utah; Colorado River near Cisco, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona) and using an expanded tree-ring network and longer calibration records than in previous efforts. They found the major drought of 2000–2004, "as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record" and "average reconstructed annual flow for the period 1844–1848 was lower." They reported "two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004," and six other periods "have a 10% or greater chance of being drier." In addition, their work revealed "longer duration droughts have occurred in the past" and "the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906–1995 average."

"Overall," the three researchers observed, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." Woodhouse *et al*. concluded "droughts more severe than any 20th to 21st century event occurred in the past," a finding entirely contrary to the climate model projection that global warming promotes longer-lasting droughts of greater severity. The real-world record of Upper Colorado River Basin droughts instead suggests such climatic conditions are more strongly associated with the much colder temperatures that characterized the Little Ice Age.

Woodhouse and Lukas (2006) developed "a network of 14 annual streamflow reconstructions, 300–600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies." Their expanded streamflow reconstructions indicated "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries." The scientists reported "multi-year drought events more severe than the 1950s drought have occurred" and "the greatest frequency of extreme low flow events occurred in the 19th century," with a "clustering of extreme event years in the 1840s and 1850s."

Meko *et al*. (2007) used a newly developed network of tree-ring sites located within the Upper Colorado River Basin, consisting of tree-ring samples from living trees augmented by similar samples obtained from logs and dead standing trees (remnant wood), to extend the record of reconstructed annual flows of the Colorado River at Lees Ferry, Arizona, into the Medieval Warm Period, during which they say "epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North America."

"The most prominent feature of the smoothed long-term reconstruction," Meko *et al*. write, "is the major period of low flow in the mid-1100s," which "25-year running mean occurred in AD 1130–1154." For this level of smoothing, they reported, "conditions in the mid-1100s in the UCRB were even drier than during the extremely widespread late-1500s North American mega-drought (e.g., Stahle *et al*., 2000)." For comparison, they observed "if 'normal' is defined as the observed mean annual flow for 1906–2004, the anomalous flow for AD 1130–1154 was less than 84% of normal," whereas "the lowest 25-year mean of observed flows (1953–1977) was 87% of normal." The authors further noted the 80% confidence band of their data "suggests a greater than 10% probability that the true mean for AD 1130–1154 was as low as 79% of normal." Additionally, the seven scientists reported "a detailed view of the time series of annual reconstructed flow reveals that the mid-1100s is characterized by a series of multi-year low-flow pluses imbedded in a generally dry 62-year period (1118–1179)," and "the key drought signature is a stretch of 13 consecutive years of below normal flow (1143–1155)." They also noted "in no other period of the reconstruction was flow below normal for more than 10 consecutive years, and the longest stretch of consecutive dry years in the reconstruction for the modern instrumental period (post 1905) was just 5 years."

Gray *et al*. (2011) observed "over the past decade severe drought conditions in the western United States have driven a growing interest in the range of natural hydrologic variability that has occurred over past centuries to millennia," as have "concerns related to the detection and prediction of anthropogenic climate-change impacts." The authors noted in order to know how unusual or unprecedented certain aspects of climate may have been recently, one must know how they varied over past centuries to millennia, when man's influence on them was minimal or non-existent. Against this backdrop, the three U.S. researchers derived millennial-length records of water year (October–September) streamflow for three key Upper Colorado River tributaries—the White, Yampa, and Little Snake Rivers—based on tree-ring data they obtained from 75 preexistent chronologies for sites scattered throughout the region, where each chronology was derived from average annual ring-widths of at least 15 and as many as 80 trees per site.

They found "as in previous studies focused on the Upper Colorado River system as a whole (e.g., Meko *et al*., 2007)," the sub-basin reconstructions "show severe drought years and extended dry periods well outside the range of observed flows." Although they noted 1902 and 2002 "were among the most severe in the last ~1,000 years," they found "pre-instrumental dry events often lasted a decade or longer with some extended low-flow regimes persisting for 30 years or more." In addition, their research "shows anomalous wetness in the 20th century, a finding that has been well documented in the Colorado River basin and surrounding areas (Gray *et al*., 2004, 2007; Woodhouse *et al*., 2006; Watson *et al*., 2009)."

In an additional study from the Colorado Plateau region with implications for drought in the entire western United States, Routson *et al*. (2011) reported "many southwestern United States high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than we have experienced during the historical period (e.g., Woodhouse and Overpeck, 1998; Cook *et al*., 2004, 2010; Meko *et al*., 2007).” They observed “the medieval interval (ca. AD 900 to 1400), a period with relatively warm Northern Hemisphere temperatures, has been highlighted as a period in western North America with increased drought severity, duration and extent (e.g., Stine, 1994; Cook *et al*., 2004, 2010; Meko *et al*., 2007; Woodhouse *et al*., 2010),” and “the mid-12th century drought associated with dramatic decreases in Colorado River flow (Meko *et al*., 2007), and the ‘Great Drought’ associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region (Douglass, 1929), all occurred during the medieval period.” These observations suggest significant Northern Hemispheric warmth tends to produce western North America megadroughts.

Routson *et al*. used a new tree-ring record derived from living and remnant bristlecone pine wood from the headwaters region of the Rio Grande River in Colorado (USA), along with other regional records, to evaluate “periods of unusually severe drought over the past two millennia (268 BC to AD 2009).” The three researchers reported their work “reveals two periods of enhanced drought frequency and severity relative to the rest of the record,” and “the later period, AD ~1050–1330, corresponds with medieval aridity well documented in other records.” The researchers reported “the earlier period is more persistent (AD ~1–400), and includes the most pronounced event in the ... chronology: a multi-decadal-length drought during the 2nd century,” which “includes the unsmoothed record’s driest 25-year interval (AD 148–173) as well as a longer 51-year period, AD 122–172, that has only two years with ring width slightly above the long-term mean,” Also, “the smoothed chronology shows the periods AD 77–282 and AD 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-year record.” They observed this second century drought “impacted a region that extends from southern New Mexico north and west into Idaho.”

Routson *et al*. reported “reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity,” and “available data also suggest that the Northern Hemisphere may have been warm during both intervals.” Routson *et al*. suggested the southwestern United States could experience similar or even more severe megadroughts in the future, as they suspect it will continue to warm in response to continued anthropogenic CO_2 emissions. If global warming is in fact the major cause of western USA drought, then it must be significantly cooler now than it was during those two prior multicentury warm periods, since we have not yet experienced droughts anywhere near the severity or duration of those that occurred in the Roman and Medieval Warm Periods.

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7.4.4.3.3.6 Arizona/New Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Arizona and New Mexico region of the United States.

Ni *et al*. (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division of Arizona and New Mexico from a network of 19 tree-ring chronologies. They determined “sustained dry periods comparable to the 1950s drought” occurred in “the late 1000s, the mid 1100s, 1570–97, 1664–70, the 1740s, the 1770s, and the late 1800s.” They also noted the 1950s drought “only lasted from approximately 1950 to 1956,” whereas the sixteenth-century megadrought lasted more than four times longer.

Rasmussen *et al*. (2006) derived a record of regional relative moisture from variations in the annual band thickness and mineralogy of two columnar stalagmites collected from Carlsbad Cavern and Hidden Cave in the Guadalupe Mountains near the New Mexico/Texas border. They discovered both records “suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record,” confirming the significant droughts and floods of recent times are certainly not unprecedented during the past millennium or more.

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7.4.4.3.3.7 Multiple States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to multiple-state regions in the western United States.

Several studies have examined historical drought trends across multiple states in the western United States. Gray *et al*. (2003), for example, examined 15 tree ring-width chronologies used in previous reconstructions of drought for evidence of low-frequency variations in five regional composite precipitation histories in the central and southern Rocky Mountains. They found “strong multidecadal phasing of moisture variation was present in all regions during the late 16th-century megadrought,” and “oscillatory modes in the 30–70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." They speculated "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase Pacific Decadal Oscillation with the warm phase Atlantic Multidecadal Oscillation," which they envisioned as having happened in both the severe 1950s drought and the late sixteenth-century megadrought. This suggests episodes of extreme dryness in this part of the country may be driven in part by naturally recurring climate "regime shifts" in the Pacific and Atlantic Oceans.

Seager (2007) also suggested ocean oscillations might bear a good deal of the blame for large-scale drought in the western United States. Seager studied the global context of the drought that affected nearly the entire United States, northern Mexico, and the Canadian Prairies—but most particularly the American West—between 1998 and 2004. Based on atmospheric reanalysis data and ensembles of climate model simulations forced by global or tropical Pacific sea surface temperatures over the period January 1856 to April 2005, Seager compared the climatic circumstances of the recent drought with those of the five prior great droughts of North America: the Civil War drought of 1856–1865, the 1870s drought, the 1890s drought, the great Dust Bowl drought, and the 1950s drought. Seager reported the 1998–2002 period of the recent drought "was most likely caused by multiyear variability of the tropical Pacific Ocean," noting the recent drought "was the latest in a series of six persistent global hydroclimate regimes, involving a persistent La Niña-like state in the tropical Pacific and dry conditions across the midlatitudes of each hemisphere."

No aspect of Seager's study implicated global warming, either CO_2-induced or otherwise, as a cause of or contributor to the turn-of-the-twentieth-century drought that affected large portions of North America. Seager noted, for example, "although the Indian Ocean has steadily warmed over the last half century, this is not implicated as a cause of the turn of the century North American drought because the five prior droughts were associated with cool Indian Ocean sea surface temperatures." In addition, the five earlier great droughts occurred during periods when the mean global temperature was significantly cooler than what it was during the last great drought.

Woodhouse (2004) covered the western United States, reporting what is known about natural hydroclimatic variability throughout the region. Woodhouse described several major droughts that occurred there during the past three millennia, all but the last century of which had atmospheric CO_2 concentrations that never varied by more than about 10 ppm from a mean value of 280 ppm.

For comparative purposes, Woodhouse began by noting "the most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts." The first of these droughts lasted "most of the decade of the 1930s" and "occurred in several waves," while the latter "also occurred in several waves over the years 1951–1956." Far more severe than either of these two droughts was the sixteenth century megadrought, which lasted from 1580 to 1600 and included northwestern Mexico in addition to the southwestern United States and the western Great Plains. There was also The Great Drought, which spanned the last quarter of the thirteenth century and was actually the last in a series of three thirteenth-century droughts, the first of which may have been even more severe than the last. In addition, Woodhouse noted there was a period of remarkably sustained drought in the second half of the twelfth century.

According to Woodhouse, "the 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records." This subset does not even begin to approach the level of drought severity and duration experienced in prior centuries and millennia, which fact was confirmed in a separate paper published by Woodhouse with four coauthors six years later (Woodhouse *et al.*, 2010). It would take a drought much more extreme than the most extreme droughts of the twentieth century to propel the western United States and adjacent portions of Canada and Mexico into a truly unprecedented state of dryness.

Benson *et al.* (2007) reviewed and discussed the possible impacts of early-eleventh, middle-twelfth, and late-thirteenth century droughts on three Native American cultures that occupied parts of the western United States (Anasazi, Fremont, Lovelock) plus another culture that occupied parts of southwestern Illinois (Cahokia). According to the authors, "population declines among the various Native American cultures were documented to have occurred either in the early-11th, middle-12th, or late-13th centuries"—AD 990–1060, 1135–1170, and 1276–1297, respectively—and "really extensive droughts impacted the regions occupied by these prehistoric Native Americans during one or more of these three time periods." In particular, they found the middle-twelfth century drought "had the strongest impact on the Anasazi and Mississippian Cahokia cultures," noting "by AD 1150, the Anasazi had abandoned 85% of their great houses in the Four Corners region and most of their village sites, and the Cahokians had abandoned one or more of their agricultural support centers, including the large Richland farming complex." In addition, "the sedentary Fremont appear to have abandoned many of their southern area habitation sites in the greater Uinta Basin area by AD 1150 as well as the eastern Great Basin and the Southern Colorado Plateau," so "in some sense, the 13th century drought may simply have 'finished off' some cultures that were already in decline." Benson *et al.* found these "major reductions in prehistoric Native American habitation sites/population" occurred during a period of "anomalously warm" climatic conditions, which characterized the Medieval Warm Period throughout much of the world at that time.

Two papers by E.R. Cook provide additional information relevant to western United States drought trends. In the first, Cook *et al.* (2004) developed a 1,200-year history of drought for the western half of the country and adjacent parts of Canada and Mexico (hereafter the "West"), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66% of them) possessed data extending back to AD 800. This reconstruction revealed "some remarkable earlier increases in aridity that dwarf the comparatively short-duration current drought in the 'West.'" Specifically, they reported "the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occur during a ~400 year interval of overall elevated aridity from AD 900 to 1300," which they observed was "broadly consistent with the Medieval Warm Period."

Commenting on the strength and severity of Medieval drought, the five scientists reported "the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests that anomalously warm climate conditions during that time may have contributed to the development of more frequent and persistent droughts in the 'West,'" as well as the megadrought Rein *et al.* (2004) discovered to have occurred in Peru at about the same time (AD 800–1250). After citing nine other studies providing independent evidence of drought during this time period for various sub-regions of the West, Cook *et al.* warned "any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America" and "future droughts in the 'West' of similar duration to those seen prior to AD 1300 would be disastrous."

It is important to note such an unfortunate fate could befall the western United States even in the absence of CO_2-induced global warming, for the millennial-scale oscillation of climate that brought the world the Medieval Warm Period (which was not CO_2-induced) could be repeating itself during the possibly still-ongoing development of the Current Warm Period. In addition, if the association between global warmth and drought in the western United States is indeed robust, current world temperatures must still be far below those experienced during large segments of the Medieval Warm Period, as no drought of Medieval magnitude has accompanied the modern rise in temperature.

In the second of the two papers, Cook *et al.* (2010) wrote "IPCC Assessment Report 4 model projections suggest that the subtropical dry zones of the world will both dry and expand poleward in the future due to greenhouse warming," and "the US southwest is particularly vulnerable in this regard and model projections indicate a progressive drying there out to the end of the 21st century." They observed "the USA has been in a state of drought over much of the West for about 10 years now," and "while severe, this turn of the century drought has not yet clearly exceeded the severity of two exceptional droughts in the 20th century." As a result, "while the coincidence between the turn of the century drought and projected drying in the Southwest is cause for concern, it is premature to claim that the model projections are correct."

This fact is understood when the "turn of the century drought" is compared with the two "exceptional droughts" that preceded it by a few decades. Based on gridded instrumental Palmer Drought Severity indices for tree-ring reconstruction extending back to 1900, Cook *et al.* (2010) calculated the turn-of-the-century drought had its greatest Drought Area Index value of 59% in the year 2002, whereas the Great Plains/Southwest drought covered 62% of the United States in its peak year of 1954 and the Dust Bowl drought covered 77% of the nation in 1934. In terms of drought duration, on the other hand, things are not quite as clear. Stahle *et al.* (2007) estimated the first two droughts lasted for 12 and 14 years, respectively; Seager *et al.* (2005) estimated them to have lasted for eight and 10 years; and Andreadis *et al.* (2005) estimated them to have lasted for seven and eight years. This yields means of nine and 11 years for the two exceptional droughts, compared with 10 or so years for the turn-of-the-century drought, which makes the latter drought not unprecedented even in the twentieth century.

A comparison of the turn-of-the-century drought with droughts of the prior millennium provides clarity on the topic. Cook *et al*. (2010) noted "perhaps the most famous example is the 'Great Drouth' (sic) of AD 1276–1299 described by A.E. Douglass (1929, 1935)." This 24-year drought was eclipsed by the 38-year drought found by Weakley (1965) to have occurred in Nebraska from AD 1276 to 1313, which the authors say "may have been a more prolonged northerly extension of the 'Great Drouth.'" Even these multidecade droughts pale in comparison to the "two extraordinary droughts discovered by Stine (1994) in California that lasted more than two centuries before AD 1112 and more than 140 years before AD 1350." Each of these megadroughts, as Cook *et al*. (2010) described them, occurred "in the so-called Medieval Warm Period." And they report "all of this happened *prior to the strong greenhouse gas warming that began with the Industrial Revolution* [emphasis in original]."

Given the above-referenced medieval megadroughts "occurred without any need for enhanced radiative forcing due to anthropogenic greenhouse gas forcing"—because there was none at that time—Cook *et al*. (2010) concluded "there is no guarantee that the response of the climate system to greenhouse gas forcing will result in megadroughts of the kind experienced by North America in the past." Those who continue to claim global warming will trigger medieval-like megadroughts also must acknowledge the Medieval Warm Period of a thousand years ago had to have been much warmer than the Current Warm Period has been to date.

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7.4.4.3.4 Southern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the southern United States.

Writing as background for their study, Chen *et al.* (2012) reported "the IPCC (2007) and the U.S. Climate Report (Karl *et al.*, 2009) predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water," with the forecast result "it is likely that drought intensity, frequency, and duration will increase in the future for the Southern United States." To test the validity of this claim, Chen *et al.* used the standard precipitation index (SPI) to characterize drought intensity and duration throughout the Southern United States (SUS) over the past century.

According to the nine researchers, the results indicated there were "no obvious increases in drought duration and intensity during 1895–2007." Instead, they found "a slight (not significant) decreasing trend in drought intensity." They noted "although reports from IPCC (2007) and the U.S. Climate Report (Karl *et al.*, 2009) indicated that it is likely that drought intensity, frequency, and duration will increase in the future for the SUS, we did not find this trend in the historical data." They also noted, although "the IPCC (2007) and U.S. Climate Report predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water," they "found no obvious increase in air temperature for the entire SUS during 1895–2007."

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7.4.4.3.5 Entire Conterminous United States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the conterminous United States.

Andreadis and Lettenmaier (2006) examined twentieth-century trends in soil moisture, runoff, and drought over the conterminous United States with a hydroclimatological model forced by real-world measurements of precipitation, air temperature, and wind speed over the period 1915–2003. This work revealed "droughts have, for the most part, become shorter, less frequent, less severe, and cover a smaller portion of the country over the last century."

Using the self-calibrating Palmer (1965) drought severity index (SCPDSI), as described by Wells *et al.* (2004), Van der Schrier *et al.* (2006) constructed maps of summer moisture availability across a large portion of North America (20–50°N, 130–60°W) for the period 1901–2002 with a spatial latitude/longitude resolution of 0.5° x 0.5°. This revealed for the area as a whole, "the 1930s and 1950s stand out as times of persistent and exceptionally dry conditions, whereas the 1970s and the 1990s were generally wet." The authors reported "no statistically significant trend was found in the mean summer SCPDSI over the 1901–2002 period, nor in the area percentage with moderate or severe moisture excess or deficit." Moreover, they could not find a single coherent area within the SCPDSI maps that "showed a statistically significant trend over the 1901–2002 period."

Fye *et al.* (2003) developed gridded reconstructions of the summer (June–August) basic Palmer Drought Severity Index over the continental United States, based on "annual proxies of drought and wetness provided by 426 climatically sensitive tree-ring chronologies." This work revealed the greatest twentieth century moisture anomalies across the United States were the 13-year pluvial in the West in the early part of the century and the epic droughts of the 1930s (the Dust Bowl years) and 1950s, which lasted 12 and 11 years, respectively. Comparing these events to earlier wet and dry periods, they made the following points.

The 13-year pluvial from 1905 to 1917 had three earlier analogs: an extended 16-year pluvial from 1825 to 1840, a prolonged 21-year wet period from 1602 to 1622, and a 10-year pluvial from 1549 to 1558. The 11-year drought from 1946 to 1956, on the other hand, had at least 12 earlier analogs in terms of location, intensity, and duration, but the Dust Bowl drought was greater than all of them—except for a sixteenth century "megadrought" that lasted some 18 years and was, in the words of Fye *et al.*, "the most severe sustained drought to impact North America in the past 500 to perhaps 1000 years."

Stahle *et al.* (2000) developed a long-term history of North American drought from reconstructions of the Palmer Drought Severity Index based on analyses of many lengthy tree-ring records. This history also showed the 1930s Dust Bowl drought in the United States was eclipsed by the sixteenth century megadrought. This incredible period of dryness, as they described it, persisted "from the 1540s to 1580s in Mexico, from the 1550s to 1590s over the [U.S.] Southwest, and from the 1570s to 1600s over Wyoming and Montana." In addition, it "extended across most of the continental United States during the 1560s," and it recurred with greater intensity over the Southeast during the 1580s to 1590s. Stahle *et al.* reported "the 'megadrought' of the 16th century far exceeded any drought of the 20th century." A "precipitation reconstruction for western New Mexico suggests that the 16th-century drought was the most extreme prolonged drought in the past 2000 years."

Herweijer *et al.* (2006) noted "drought is a recurring major natural hazard that has dogged civilizations through time and remains the 'world's costliest natural disaster.'" With respect to the twentieth century, for example, they reported the "major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA." They also noted "these events are not unique to the twentieth century." They described three periods of widespread and persistent drought in the latter half of the nineteenth century—1856–1865 (the "Civil War" drought), 1870–1877, and 1890–1896—based on evidence obtained from proxy, historical, and instrumental data.

With respect to the first of these mid- to late-nineteenth century droughts, Herweijer *et al.* found it "is likely to have had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl drought." In addition, they reported "drought conditions during the Civil War, 1870s and 1890s droughts were not restricted to the summer months, but existed year round, with a large signal in the winter and spring months."

The three researchers cited the work of Cook and Krusic (2004), who constructed a North American Drought Atlas using hundreds of tree-ring records. This atlas revealed what Herweijer *et al.* described as "a 'Mediaeval Megadrought' that occurred from AD 900 to AD 1300," along with "an abrupt shift to wetter conditions after AD 1300, coinciding with the 'Little Ice Age', a time of globally cooler temperatures" that ultimately gave way to "a return to more drought-prone conditions beginning in the nineteenth century."

The broad picture emerging from the work of Herweijer *et al.* is one where the most severe North American droughts of the past millennium were associated with the globally warmer temperatures of the Medieval Warm Period plus the initial stage of the globally warmer Current Warm Period. Superimposed upon this low-frequency behavior, Herweijer *et al.* found evidence for a "linkage between a colder eastern equatorial Pacific and persistent North American drought over the last 1000 years," further noting "Rosby wave propagation from the cooler equatorial Pacific amplifies dry conditions over the USA." In addition, after using "published coral data for the last millennium to reconstruct a NINO 3.4 history," they applied "the modern-day relationship between NINO 3.4 and North American drought ... to recreate two of the severest Mediaeval 'drought epochs' in the western USA."

How is it that simultaneous global-scale warmth and regional-scale cold combine to produce the most severe North American droughts? One possible element is variable solar activity, which, as suggested in Chapter 3 of this report, drives the millennial-scale oscillation of climate that produced the global Medieval Warm Period, Little Ice Age, and Current Warm Period. When solar activity is in an ascending mode, the globe as a whole warms, but at the same time, to quote from Herweijer *et al.*'s concluding sentence, increased irradiance typically "corresponds to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions."

These observations imply the most severe North American droughts should occur during major multi-centennial global warm periods, as has been observed to be the case. Since the greatest such droughts of the Current Warm Period have not approached the severity of those that occurred during the Medieval Warm Period, one might logically infer the global temperature of the Current Warm Period is not as high as the global temperature that prevailed throughout the Medieval Warm Period.

Stahle *et al.* (2007) used "an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook *et al*., 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America" since AD 1300. In discussing the Current Warm Period, Stahle *et al*. observed, "the Dust Bowl drought of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America," citing the studies of Worster (1979), Diaz (1983), and Fye *et al.* (2003). During the Little Ice Age, by contrast, Stahle *et al.* found three megadroughts, which they defined as "very large-scale drought[s] more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle *et al*., 2000)." They reported "much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine, 1994; Laird *et al*., 2003; Cook *et al*., 2004)." These latter megadroughts were so impactful Stahle *et al.* referred to them as "no-analog Medieval mega-droughts."

Herweijer *et al.* (2007) used Palmer Drought Severity Index data found in the North American Drought Atlas prepared by Cook and Krusic (2004), derived from a network of drought-sensitive tree-ring chronologies (some stretching back to AD 800 and encompassing the Medieval Warm Period), placing into a longer perspective "the famous droughts of the instrumental record (i.e., the 1930s Dust Bowl and the 1950s Southwest droughts)." They reported, "the famous droughts of the instrumental era are dwarfed by the successive occurrence of multidecade-long 'megadroughts' in the period of elevated aridity between the eleventh and fourteenth centuries AD." They noted medieval megadroughts, although more extreme in terms of persistence, "share the severity and spatial distribution characteristics of their modern-day counterparts." This led them to conclude the mechanism responsible for major North American droughts of the twentieth century "is synonymous with that underlying the megadroughts of the medieval period," the only difference being the degree of persistence of the forcing that caused them.

What, then, is the common denominator shared by the major North American droughts of the modern and medieval periods?

"With ENSO showing a pronounced signal in the gridded drought reconstructions of the last millennium, both in terms of its link to the leading spatial mode, and the leading time scales of drought variability," Herweijer *et al.* concluded "medieval megadroughts were forced by protracted La Niña-like tropical Pacific sea surface temperatures." In addition, they demonstrated "a global hydroclimatic 'footprint' of the medieval era revealed by existing paleoclimatic archives from the tropical Pacific and ENSO-sensitive tropical and extratropical land regions." They observed "this global pattern matches that observed for modern-day persistent North American drought," namely, "a La Niña-like tropical Pacific."

A number of paleoclimate studies demonstrate when Earth was significantly warmer than the present, such as during the Medieval Warm Period, ENSO events were often substantially reduced and sometimes even absent (see Chapter 4). Consequently, since the North American droughts of the Medieval Warm Period dwarfed those of the Current Warm Period—with both produced by La Niña-like conditions (which are more prevalent during times of greater warmth)—it follows that the Medieval Warm Period was significantly warmer than the Current Warm Period.

Climate models typically project CO_2-induced global warming will result in more severe droughts. The much more severe and sustained megadroughts of the Little Ice Age appear to render this claim dubious.

Although the severe and sustained no-analogue megadroughts of the Medieval Warm Period would appear to bolster the climate models' projections, the substantially more severe droughts of that period—if they were indeed related to high global air temperatures—would suggest it is not nearly as warm today as it was during the Medieval Warm Period, when there was far less CO_2 in the air than there is today. These observations undercut the more fundamental claim that the historical rise in the air's

CO_2 content has been responsible for what the IPCC and others have described as unprecedented twentieth century global warming.

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7.4.5 Central and South America

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the regions of Central and South America.

Webster *et al*. (2007) removed an active stalagmite (MC01) from the entrance chamber of Macal Chasm—a cave on the Vaca Plateau west of the Rio Macal in the Cavo District of Belize near the border with Guatemala (~17°N, 89°W)—from which they obtained "reliably dated reflectance, color, luminescence, and C and O stable isotope records for the period from 1225 BC to the present." Upon examination of the record, the authors report the interval "from AD 750 to 1150 was the most prolonged dry phase in our 3300-year record." This time period corresponds well with the MWP's mean time of occurrence around the globe, which, Webster *et al*. observed, "coincided with the collapse of the Maya civilization." They observed their data depicted "a series of droughts centered at about AD 780, 910, 1074, and 1139," with "successive droughts increasing in severity."

The seven scientists reported the results of their investigations "add to a growing body of evidence suggesting that severe dryness affected a broad region of Mesoamerica and contributed to the collapse of the Maya civilization during the Late Classic period." Consequently, although the warmth of the MWP benefited Norse settlers on Greenland, its dryness across a broad swath of Mesoamerica spelled an end to the indigenous civilization of that region.

Morengo (2009) worked with hydro-meteorological indices for the Amazon basin and its several sub-basins "to explore long-term variability of climate since the late 1920s and the presence of trends and/or cycles in rainfall and river indices in the basin." These analyses were based on northern and southern Amazonian rainfall data originally developed by Marengo (1992) and Marengo and Hastenrath (1993), and subsequently updated by Marengo (2004). According to the Brazilian researcher, "no systematic unidirectional long-term trends towards drier or wetter conditions [were] identified." Instead, he found "the rainfall and river series show variability at inter-annual scales." Of the patterns he uncovered, Morengo observed they are "characteristic of decadal and multi-decadal modes," which he describes as "indicators of natural climate variability" linked to the El Niño/Southern Oscillation, "rather than any unidirectional trend towards drier conditions (as one would expect, due to increased deforestation or to global warming)."

Minetti *et al*. (2010) evaluated the annual occurrence of droughts and their persistence in what they described as "an attempt to determine any aspects of the impact of global warming." They examined a regional inventory of monthly droughts for the portion of South America located south of approximately 22°S latitude, dividing the area of study into six sections (the central region of Chile plus five sections making up most of Argentina).

They identified "the presence of long favorable tendencies [1901–2000] regarding precipitations or the inverse of droughts occurrence are confirmed for the eastern Andes Mountains in Argentina with its five sub-regions (Northwest Argentina, Northeast Argentina, Humid Pampa, West-Centre Provinces and Patagonia) and the inverse over the central region of Chile." From the middle of 2003 to 2009, however, they reported "an upward trend in the occurrence of droughts with a slight moderation over the year 2006." They additionally noted the driest single-year periods were 1910–1911, 1915–1916, 1916–1917, 1924–1925, and 1933–1934, suggesting twentieth century global warming has not promoted an abnormal increase in droughts in the southern third of South America.

Mundo *et al*. (2012) employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of Argentina's Neuquen River over the 654-year period AD 1346–2000. According to the eight researchers, in terms of the frequency, intensity, and duration of droughts and pluvial events, "the 20th century contains some of the driest and wettest annual to decadal-scale events in the last 654 years." They also noted "longer and more severe events were recorded in previous centuries." Importantly, the bulk of the 554 years preceding the twentieth century were part of the much colder Little Ice Age, and it would thus appear the global warming of the past century has brought Argentina's Neuquen River less extreme streamflow conditions.

Masiokas *et al*. (2012) developed the first reconstruction and quantitative analysis of variations in snow accumulation for the past eight-and-a-half centuries in the Andes between 30° and 37°S. The record was based on "instrumental rainfall and streamflow data from adjacent lowlands, a variety of documentary records, and century-long tree-ring series of precipitation-sensitive species from the western side of the Andes," representing "the first attempt to reconstruct annually-resolved, serially complete snowpack variations spanning most of the past millennium in the Southern Hemisphere." This record "allows testing the relative severity of recent 'extreme' conditions in a substantially longer context."

The eight researchers report "variations observed in the last 60 years are not particularly anomalous when assessed in a multi-century context," noting both extreme high and low snowpack values "have not been unusual when assessed in the context of the past eight centuries." They found "the most extreme dry decades are concentrated between the late 16th century and the mid-18th century," and there were "decade-long periods of high snowpack levels that equaled or probably surpassed those recorded during the past six decades."

The results of the several studies described above indicate the warming of the twentieth and early twenty-first centuries has brought nothing unusual, unnatural, or unprecedented in the way of trends in drought frequency and severity for the studied areas of South America.

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7.4.6 Global

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the entire planet.

Svensson *et al.* (2005) examined twentieth century river flow data for a group of 21 stations distributed around the globe, which they obtained from the Global Runoff Data Centre in Koblenz, Germany. Individual record lengths for the 21 stations varied from 44 to 100 years, with an average of 68 years, and the three researchers' analyses of the data consisted of computing trends in both high flows and low flows using Mann-Kendall and linear regression methods. In the case of high flows, their work revealed slightly more stations exhibiting significant negative trends (reduced flooding) than significant positive trends (increased flooding). With respect to low flows, nearly all stations showed increasing trends, approximately half of which were significant at the 90% level, indicative of a general trend of decreasing drought throughout the world.

Huntington (2006) reviewed the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and a number of other water-related parameters. He found on a globally averaged basis, "precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998)." He also reported "an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987)," and a reanalysis of those trends for the period 1920–1995 "confirmed an increase in world continental runoff during the 20th century (Labat *et al.*, 2004)." Huntington further reported "summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al.*, 2000)."

Narisma *et al.* (2007) analyzed "global historical rainfall observations to detect regions that have undergone large, sudden decreases in rainfall [that] are statistically significant at the 99% level, are persistent for at least ten years, and ... have magnitudes that are [mostly] 10% lower than the climatological normal (1901–2000 rainfall average)." Working with the gridded high-resolution (0.5 x 0.5 degrees of latitude and longitude) global precipitation dataset of Mitchell *et al.* (2004), which covers the period 1901–2000, they identified 30 drought episodes throughout the world that satisfied these stringent criteria during the twentieth century. These episodes included the sudden and prolonged Sahel drought of Africa in the late 1960s; the United States Dust Bowl of the 1930s and Southwest drought of the 1950s (which also affected parts of Mexico); the strong and persistent droughts that occurred in northeast China in the 1920s, in Kazakhstan and regions of the former Soviet Union in the late 1930s, in southeast Australia in the late 1930s, and in southern Africa and eastern Europe in the 1980s; the World War II droughts of 1937–1945; and the droughts that occurred over large regions of East India and Bangladesh in the 1950s.

Seven of the 30 severe and persistent droughts identified by Narisma *et al.* occurred during the first two decades of the twentieth century (1901–1920), seven occurred during the next two decades (1921–1940), eight during the middle two decades of the century (1941–1960), only five during the next two decades (1961–1980), and a mere three during the final two decades of the century (1981–2000). This distribution is not at all what one would have expected if the model-based thesis propounded by the

IPCC were correct.

The scientists who performed the analysis reported the 30 major droughts they identified were "mostly located in semi-arid and arid regions" that "are naturally prone to large fluctuations." The 30 major droughts of the twentieth century were therefore likely natural in all respects and hence "indicative of what could also happen in the future," as Narisma *et al*. state in their concluding paragraph.

Sheffield and Wood (2008) studied "variability and trends in soil moisture and drought characteristics, globally and regionally over the second half of the twentieth century." They used "a global soil moisture dataset derived from a model simulation of the terrestrial hydrologic cycle," which was "driven by a hybrid observation-reanalysis-based meteorological dataset." This work revealed "an overall increasing trend in global soil moisture, driven by increasing precipitation, underlies the whole analysis, which is reflected most obviously over the western hemisphere and especially in North America." In addition, they determined "trends in drought characteristics are predominantly decreasing" and "concurrent changes in drought spatial extent are evident, with a global decreasing trend of -0.021% to -0.035% per year." They also discovered "a switch in later years to a drying trend, globally and in many regions," which they say was "concurrent with increasing temperatures." This drying trend was not strong enough to overpower the increasing trend of global soil moisture over the entire half-century of their analysis.

In a subsequent analysis of the same time period, Sheffield *et al*. (2009) used "observation-driven simulations of global terrestrial hydrology and a cluster algorithm that searches for spatially connected regions of soil moisture" to identify "296 large scale drought events (greater than 500,000 km^2 and longer than 3 months) globally for 1950–2000." They reported "the mid-1950s showed the highest drought activity and the mid-1970s to mid-1980s the lowest activity."

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7.5 Floods

Climate model simulations generally predict a future with more frequent and more severe floods in response to CO_2-induced global warming. Confirming such predictions has remained an elusive task, according to the IPCC, which claims in its most recent report "there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale" (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

Contrary to the IPCC's assessment of the situation, there exists a large body of scientific research on this topic. According to that research, as outlined in the subsections that follow, there is much evidence to conclude CO_2-induced global warming is not currently increasing the frequency and/or magnitude of floods, nor will it likely impact such phenomena in the future.

7.5.1 Africa

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Africa.

Noting "droughts and floods represent extreme conditions, and are precisely those that are foreseen to increase in [the] future with global change," Heine (2004) analyzed soil sequences and slackwater deposits laid down over the course of the Holocene in valleys of the Namibian Desert, located between southern Angola and South Africa along the South Atlantic Ocean and stretching inland about 200 km, where it abuts on Africa's Great Western Escarpment. The author reports "during the Holocene, slackwater deposits of the Namib Desert valleys accumulated between ca. 10 and 8 ka BP and between ca. 2 and 0 ka BP." Of the latter period, he notes "the youngest accumulation phase occurred during the Little Ice Age (LIA, ca. AD 1300 to 1850)." In addition, he finds "the biggest flash floods of the LIA, in most catchments, experienced water levels in the valleys that exceeded the most extreme floods of the last 100 to 150 years."

Commenting on the nature of the LIA itself, Heine reports "maximum LIA cooling occurred around AD 1700 (ca. -1°C)," noting "this cold period was coeval with cool events recorded in a large variety of proxy data from all sites over southern Africa and from corals in the ocean off southwestern Madagascar (Tyson *et al*., 2001)."

In Africa's Namib Desert, the greatest floods of the past two millennia occurred during its coldest period, the Little Ice Age, with nothing to compare to them during what the IPCC typically describes as the warmest portion of the past two millennia; i.e., the latter part of the twentieth century.

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7.5.2 Asia

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Asia.

Cluis and Laberge (2001) analyzed the flow records of 78 rivers distributed throughout the entire Asia-Pacific region to see if there had been any enhancement of Earth's hydrologic cycle coupled with an increase in variability that might have led to more floods between the mean beginning and end dates of the flow records: 1936 ± 5 years and 1988 ± 1 year, respectively. The two scientists determined mean river discharges were unchanged over this period in 67% of the cases investigated; where they found trends, 69% of them were downward. In addition, maximum river discharges were unchanged in 77% of the cases investigated; where there were trends, 72% of them were downward. Contrary to model-based claims of global warming leading to more frequent and more severe flooding, the two researchers observed no changes in these flood characteristics in the majority of the rivers they studied; and where there were changes, more of them were of the type that typically leads to less flooding and less severe floods.

Kale *et al.* (2003) conducted geomorphic studies of slackwater deposits in the bedrock gorges of the Tapi and Narmada Rivers of central India, assembling long chronologies of large floods of these rivers. They found "since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837." With respect to large floods on the Narmada River, they reported at least nine or ten floods between the beginning of the Christian era and AD 400; between AD 400 and 1000 they documented six or seven floods, between 1000 and 1400 about eight or nine floods, and after 1950 three more such floods. On the basis of texture, elevation, and thickness of the flood units, they conclude "the periods AD 400–1000 and post-1950 represent periods of extreme floods."

What do these findings imply about the effects of global warming on central India flood events? The post-1950 period is often claimed by the IPCC to have been the warmest of the past millennium, and it has indeed experienced some extreme floods. However, the flood characteristics of the AD 400–1000 period are described in equivalent terms, and this was a rather cold climatic interval known as the Dark Ages Cold Period (see, for example, McDermott *et al*. (2001) and Andersson *et al*. (2003)). In addition, the most extreme flood in the much shorter record of the Tapi River occurred in 1837, near the beginning of one of the colder periods of the Little Ice Age. There appears to be little correlation between the flood characteristics of the Tapi and Narmada Rivers of central India and the thermal state of the global climate.

Touchan *et al*. (2003) developed two reconstructions of spring (May–June) precipitation from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia,* and *Pinus nigra*, and the other (1339–1998) based on three chronologies of *Juniperus excelsa*. The authors report these reconstructions "show clear evidence of multi-year to decadal variations in spring precipitation," with both wet and dry periods of 1–2 years duration being well distributed throughout the record. In the case of more extreme hydrologic events, they found all of the wettest 5-year periods preceded the industrial revolution, manifesting themselves at times when the air's carbon dioxide content was largely unaffected by anthropogenic CO_2 emissions.

In a study of the Upper Volga and Zapadnaya Dvina Rivers, Panin and Nefedov (2010) documented "the geomorphological and altitudinal positions of [human] occupational layers corresponding to 1224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province," identifying "a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchical rank." The two researchers report finding "low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs," because "during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in seasonal peaks in lake levels." They note "a model of past warming epochs can be the warming in the late 20th century, still continuing now." They also report finding, "in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays." In addition, their results indicate the period AD 1000–1300 hosted the greatest number of floodplain occupations of the period studied.

Panin and Nefedov state this last period and other "epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th–early current century," which they say "is forming under the effect of directed climate change." This relationship clearly implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

Davi *et al*. (2006) developed a reconstruction of streamflow that extended from 1637 to 1997, based on absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia, all of which sites were in or near the Selenge River basin, the largest river in Mongolia. Of the ten wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the ten extreme periods, respectively), once again indicative of a propensity for less flooding during the warmest portion of the 360-year period.

Jiang *et al*. (2005) analyzed pertinent historical documents to produce a 1,000-year time series of flood and drought occurrence in the Yangtze Delta of Eastern China (30 to 33°N, 119 to 122°E), whose nearly level plain averages only two to seven meters above sea level across 75% of its area and is vulnerable to flooding and maritime tidal hazards. They found alternating wet and dry episodes occurred throughout the 1,000-year period, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850).

Zhang *et al*. (2007) also developed flood and drought histories of the Yangtze Delta for the past thousand years, "from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports." They then applied "continuous wavelet transform … to detect the periodicity and variability of the flood/drought series." The results were compared with 1,000-year temperature histories of northeastern Tibet and southern Tibet. This work revealed, in the words of the researchers, that "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region." They state, "during AD 1400–1700 [the coldest portion of their record, corresponding to much of the Little Ice Age], the proxy indicators showing the annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they report "during AD 1000–1400 [the warmest portion of their record, corresponding to much of the Medieval Warm Period], relatively stable changes of climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

Zhang *et al*. (2009) utilized wavelet analysis on the decadal locust abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al*. (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al*. (2002) for the AD 950s–1950s, "to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China." The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events. The six scientists state "global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China," noting these findings "challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects." They say their results are an example of "benign effects of global warming on the regional risk of natural disasters."

Zha *et al*. (2012) conducted a paleohydrological field investigation in the central portion of the Jinghe River, the middle and upper reaches of which are located in a semiarid zone with a monsoonal climate, between Binxian county and Chunhua county of Shaanxi Province. Their analysis revealed five extraordinary palaeoflood events determined to have occurred between 4100 and 4000 years BP; these floods "corresponded exactly with palaeoflood events (4200–4000 yr BP) recorded in the middle reaches of Qishuie River," demonstrating "extraordinary flood events were common during the episode of 4200–4000 yr BP in the middle reaches of the Yellow River."

The four Chinese researchers note "during the mid-Holocene climatic optimum, global climate was warm-humid and the climate system was stable," and during this time, they say, "there were no flood records identified in the middle reaches of the Yellow river," citing the work of Huang *et al*. (2011a,b). Thereafter, however, they report "global climatic cooling events occurred at about 4200 years BP, which was also well recorded by various climatic proxies in China," citing Zhang *et al*. (2004). In addition, they write "the decline of the Neolithic Longshan Culture in the period around 4000 years BP was thought to be linked with the global cooling events," as suggested by the work of Wu *et al*. (2001, 2004, 2005)." These observations led them to conclude, "the extraordinary floods recorded in the middle reaches of the Jinghe River were linked to the global climatic events"—all of which were global cooling events..

In a study focusing on the headwater region of the Sushui River within the Yuncheng Basin in the southeast part of the middle reaches of China's Yellow River, Huang *et al*. (2007) constructed a complete catalog of Holocene overbank flooding events at a watershed scale, based on pedo-sedimentary records of the region's semiarid piedmont alluvial plains, including the color, texture, and structure of the sediment profiles, along with determinations of particle-size distributions, magnetic susceptibilities, and elemental concentrations. This work revealed six major episodes of overbank flooding. The first occurred at the onset of the Holocene, the second immediately before the mid-Holocene Climatic Optimum, and the third in the late stage of the mid-Holocene Climatic Optimum. The last three episodes coincided with "the cold-dry stages during the late Holocene." Speaking of the last of the overbank flooding episodes, they note it "corresponds with the well documented 'Little Ice Age,'" when "climate departed from its long-term average conditions and was unstable, irregular, and disastrous," which is pretty much how the Little Ice Age has been described in many other parts of the world as well.

The findings of these several Asian-based studies provide no support for the claim that global warming leads to more frequent and severe flooding. If anything, they tend to suggest just the opposite.

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7.5.3 Europe

7.5.3.1 France

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to France.

On September 8 and 9, 2002, extreme flooding of the Gardon River in southern France occurred as approximately half an average year's rainfall was received in approximately 20 hours. This flooding claimed the lives of several people and caused much damage to towns and villages situated adjacent to the river's channel. The event elicited much coverage in the press, and in the words of Sheffer *et al.* (2003a), "this flood is now considered by the media and professionals to be 'the largest flood on record,'" which record extends back to 1890.

Coincidentally, Sheffer *et al.* were in the midst of a study of prior floods of the Gardon River when the "big one" hit, and they had data spanning a much longer time period against which to compare its magnitude. Based on that data as presented in their paper, they report "the extraordinary flood of September 2002 was not the largest by any means," noting "similar, and even larger floods have occurred several times in the recent past," with three of the five greatest floods they identified to that point in time occurring over the period AD 1400–1800 during the Little Ice Age. Sheffer *et al.* state, "using a longer time scale than human collective memory, paleoflood studies can put in perspective the occurrences of the extreme floods that hit Europe and other parts of the world during the summer of 2002." That perspective clearly shows even greater floods occurred repeatedly during the Little Ice Age, the coldest period of the current interglacial.

Sheffer *et al.* (2008) analyzed geomorphic, sedimentologic, and hydrologic data associated with both historical and late Holocene floods from two caves and two alcoves of a 1,600-meter-long stretch of the Gardon River, which they hoped would provide a longer and better-defined perspective on the subject. They discovered "at least five floods of a larger magnitude than the 2002 flood occurred over the last 500 years," all of which took place, as they describe it, "during the Little Ice Age." In addition, they note "the Little Ice Age has been related to increased flood frequency in France (Guilbert, 1994; Coeur, 2003; Sheffer, 2003; Sheffer *et al.*, 2003a,b; Sheffer, 2005), and in Spain (Benito *et al.*, 1996; Barriendos and Martin Vide, 1998; Benito *et al.*, 2003; Thorndycraft and Benito, 2006a,b)."

Renard *et al.* (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high-flow and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations having a minimum record length of 40 years. They determined "at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive." At the smaller scale of hydroclimatic regions, they also discovered no significant results for most areas.

Wilhelm *et al.* (2012) note "mountain-river floods triggered by extreme precipitation events can cause substantial human and economic losses (Gaume *et al.*, 2009)," and they state "global warming is expected to lead to an increase in the frequency and/or intensity of such events (IPCC, 2007), especially in the Mediterranean region (Giorgi and Lionello, 2008)." They point out "reconstructions of geological records of intense events are an essential tool for extending documentary records beyond existing observational data and thereby building a better understanding of how local and regional flood hazard patterns evolve in response to changes in climate."

Wilhelm *et al.* analyzed the sediments of Lake Allos, a 1-km-long by 700-m-wide high-altitude lake in the French Alps (44°14'N, 6°42'35'E), by means of both seismic survey and lake-bed coring, carrying out numerous grain size, geochemical, and pollen analyses of the sediment cores they obtained in conjunction with a temporal context derived using several radionuclide dating techniques. The 13 French researchers report their investigations revealed the presence of 160 graded sediment layers over the last 1,400 years, and comparisons of the most recent of these layers with records of historic floods suggest the sediment layers are indeed representative of significant floods that were "the result of intense meso-scale precipitation events." Of special interest is their finding of "a low flood frequency during the Medieval Warm Period and more frequent and more intense events during the Little Ice Age," which meshes nicely with the results of an analysis of a Spanish lake sediment archive that allowed Moreno *et al.* (2008) to infer "intense precipitation events occurred more frequently during the Little Ice Age than they did during the Medieval Warm Period."

Wilhelm *et al*. additionally state "the Medieval Warm Period was marked by very low hydrological activity in large rivers such as the Rhone (Arnaud *et al*., 2005; Debret *et al*., 2010), the Moyenne Durance (Miramont *et al*., 1998), and the Tagus (Benito *et al*., 2003), and in mountain streams such as the Taravilla lake inlet (Moreno *et al*., 2008)." Of the Little Ice Age, they write, "research has shown higher flood activity in large rivers in southern Europe, notably in France (Miramont *et al*., 1998; Arnaud *et al*., 2005; Debret *et al*., 2010), Italy (Belotti *et al*., 2004; Giraudi, 2005) and Spain (Benito *et al*., 2003), and in smaller catchments (e.g., in Spain, Moreno *et al*., 2008)."

Wilhelm *et al*. conclude their study shows "sediment sequences from high altitude lakes can provide reliable records of flood-frequency and intensity-patterns related to extreme precipitation events," warning "such information is required to determine the possible impact of the current phase of global warming."

Pirazzoli (2000) analyzed tide-gauge and meteorological data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions and strong surge winds in this region "are becoming less frequent." The data also revealed "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding."

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7.5.3.2 Germany

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Germany.

Burger *et al*. (2007) reviewed what is known about flooding in southwest Germany over the past three centuries. According to the six scientists, the extreme flood of the Neckar River in October 1824 was "the largest flood during the last 300 years in most parts of the Neckar catchment." They further note "it was the highest flood ever recorded in most parts of the Neckar catchment and also affected the Upper Rhine, the Mosel and Saar." They report the historical floods of 1845 and 1882 "were among the most extreme floods in the Rhine catchment in the 19th century," which they describe as "catastrophic events." The flood of 1845 "showed a particular impact in the Middle and Lower Rhine and in this region it was higher than the flood of 1824." Two extreme floods occurred in 1882, one at the end of November and another at the end of December. Of the first one, Burger *et al*. say "in Koblenz, where the Mosel flows into the Rhine, the flood of November 1882 was the fourth-highest of the recorded floods, after 1784, 1651 and 1920," with the much-hyped late-twentieth century floods of 1993, 1995, 1998, and 2002 not even meriting a mention.

Czymzik *et al*. (2010) write "assumptions about an increase in extreme flood events due to an intensified hydrological cycle caused by global warming are still under discussion and must be better verified," while noting some historical flood records indicate "flood frequencies were higher during colder periods (Knox, 1993; Glaser and Stangl, 2004), challenging the hypothesis of a correlation between the frequency of extreme floods and a warmer climate."

In June 2007 Czymzik *et al*. retrieved two sediment cores from the deepest part of Lake Ammersee in southern Germany (48°00'N, 11°07'E), which is fed primarily by the River Ammer. They analyzed the cores using what they describe as "a novel methodological approach that combines microfacies analyses, high-resolution element scanning (μ-XRF), stable isotope data from bulk carbonate samples (δ^{13}Ccarb, δ^{18}Ocarb), and X-ray diffraction (XRD) analyses (Brauer *et al*., 2009)." The six scientists determined the flood frequency distribution over the 450-year time series "is not stationary but reveals maxima for colder periods of the Little Ice Age when solar activity was reduced." They report "similar observations have been made in historical flood time series of the River Main, located approximately 200 km north of Ammersee (Glaser and Stangl, 2004), pointing to a wider regional significance of this finding."

Bormann *et al*. (2011) write, "following several severe floods in Germany during the past two decades, [the] mass media as well as scientists have debated the relative contributions of climate and/or anthropogenic processes to those floods." The three researchers utilized long time-series of stage and discharge data obtained from 78 river gauges in Germany, searching for trends in flood frequency, peak discharge, peak stage, and stage-discharge relationships, where all variables investigated had to have a temporal history of at least half a century.

They first established the nature of Germany's temperature history, noting Schonwiese (1999) identified a homogenous positive trend of 0.5–1.0°C over the course of the twentieth century, which was subsequently confirmed by Gerstengarbe and Werner (2008) and Bormann (2010). Then, in terms of land use change between 1951 and 1989, they report "agricultural area in Germany decreased from 57.8% to 53.7%, while forested areas remained almost constant." During this period, they report, "impervious areas increased sharply from 7.4% to 12.3%," and they state "this trend has continued since 1989," with impervious areas further increasing from 11.2% to 13.1%, forest areas increasing from 29.3% to 30.1%, and agricultural area decreasing from 54.7% to 52.5%. As a consequence of the net increase in impervious surfaces, they note, "runoff generation can be expected to increase and infiltration and groundwater recharge decrease," which would be expected to lead to increases in river flow and a potential for more frequent and extreme floods. However, they report "most stations analyzed on the German rivers did not show statistically significant trends in any of the metrics analyzed."

In light of these observations—plus the fact that "most decadal-scale climate-change impacts on flooding (Petrow and Merz, 2009) are small compared to historic peaks in flood occurrence (Mudelsee *et al*., 2006)"—Bormann *et al.* conclude these facts "should be emphasized in the recent discussion on the effect of climate change on flooding." The warming experienced in Germany over the past century has not led to unprecedented flooding; in fact, it has not led to any increase in flooding.

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7.5.3.3 United Kingdom

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to the United Kingdom.

Reynard *et al.* (2001) used a continuous flow simulation model to assess the impacts of potential climate and land use changes on flood regimes of the UK's Thames and Severn Rivers. As is typical of a model study, it predicted modest increases in the magnitudes of 50-year floods on these rivers when the climate was forced to change as predicted for various global warming scenarios. However, when the modelers allowed forest cover to rise concomitantly, they found this land use change "acts in the opposite direction to the climate changes and under some scenarios is large enough to fully compensate for the shifts due to climate."

To better determine what might actually happen in the real world, therefore, it is important to consider how the forested areas of the rivers' catchments might change in the future. Two things come into play here. First, if forests are deemed to be important carbon sinks for which countries may get sequestration credits, and if nations begin to employ them as such, the UK government may promote the development of new forests on much of the land in question. Second, as the air's CO_2 content continues to rise, there will be a great natural impetus for forests to expand their ranges and grow in areas where grasses now dominate the landscape. Consequently, forests may expand on the river catchments and neutralize any predicted increases in flood activity in a future high-CO_2 world.

Macklin *et al*. (2005) developed what they described as "the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ^{14}C-dated British flood deposits," They compared their reconstructed flood history "with high-resolution proxy-climate records from the North Atlantic region, northwest Europe and the British Isles to critically test the link between climate change and flooding." They determined "the majority of the largest and most widespread recorded floods in Great Britain [had] occurred during cool, moist periods," and "comparison of the British Holocene palaeoflood series ... with climate reconstructions from tree-ring patterns of subfossil bog oaks in northwest Europe also suggests that a similar relationship between climate and flooding in Great Britain existed during the Holocene, with floods being more frequent and larger during relatively cold, wet periods." In addition, they state "an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ^{14}C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods."

Noting "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments," and that "projections suggest that flooding may increase in [the] future as a result of human-induced warming," Hannaford and Marsh (2008) used the UK "benchmark network" of 87 "near-natural catchments" identified by Bradford and Marsh (2003) to conduct "a UK-wide appraisal of trends in high-flow regimes unaffected by human disturbances." They report "significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK." However, they say "there is little compelling evidence for high-flow trends in lowland areas in the south and east." They also found "in western areas, high-flow indicators are correlated with the North Atlantic Oscillation Index (NAOI)," so "recent trends may therefore reflect an influence of multi-decadal variability related to the NAOI." In addition, they state longer river flow records from five additional catchments they studied "provide little compelling evidence for long-term (>50 year) trends but show evidence of pronounced multi-decadal fluctuations."

Hanaford and Marsh also found "in comparison with other indicators, there were fewer trends in flood magnitude" and "trends in peaks-over-threshold frequency and extended-duration maxima at a gauging station were not necessarily associated with increasing annual maximum instantaneous flow." They conclude "considerable caution should be exercised in extrapolating from any future increases in runoff or high-flow frequency to an increasing vulnerability to extreme flood events."

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7.5.3.4 Spain

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Spain.

"Starting from historical document sources, early instrumental data (basically, rainfall and surface pressure) and the most recent meteorological information," Llasat *et al*. (2005) analyzed "the temporal evolution of floods in NE Spain since the 14th century," focusing on the river Segre in Lleida, the river Llobregat in El Prat, and the river Ter in Girona. The found "an increase of flood events for the periods 1580–1620, 1760–1800 and 1830–1870," and they report "these periods are coherent with chronologies of maximum advance in several alpine glaciers." In addition, calculations from their tabulated data for the aggregate of the three river basins show the mean number of what Llasat *et al*. call catastrophic floods per century for the fourteenth through nineteenth centuries was 3.55 ± 0.22, while the corresponding number for the twentieth century was only 1.33 ± 0.33.

The four Spanish researchers conclude, "we may assert that, having analyzed responses inherent to the Little Ice Age and due to the low occurrence of frequent flood events or events of exceptional magnitude in the 20th century, the latter did not present an excessively problematic scenario." Having introduced their paper with descriptions of the devastating effects of the September 1962 flash flood in Catalonia (more than 800 deaths), the August 1996 flash flood in the Spanish Pyrenees (87 deaths), and the floods of September 1992 that produced much loss of life and material damage in France and Italy, they hastened to add the more recent "damage suffered and a perception of increasing vulnerability is something very much alive in public opinion and in economic balance sheets."

Benito *et al*. (2010) reconstructed flood frequencies of the Upper Guadalentin River in southeast Spain using "geomorphological evidence, combined with one-dimensional hydraulic modeling and supported by records from documentary sources at Lorca in the lower Guadalentin catchment." The combined palaeoflood and documentary records indicate past floods were clustered during particular time periods: AD 950–1200 (10), AD 1648–1672 (10), AD 1769–1802 (9), AD 1830–1840 (6), and AD 1877–1900 (10), where the first time interval coincides with the Medieval Warm Period and the latter four fall within the confines of the Little Ice Age. By calculating mean rates of flood occurrence over each of the five intervals, a value of 0.40 floods per decade during the Medieval Warm Period and an average value of 4.31 floods per decade over the four parts of the Little Ice Age can be determined. The latter value is more than ten times greater than the mean flood frequency experienced during the Medieval Warm Period.

Barredo *et al*. (2012) say "economic impacts from flood disasters have been increasing over recent decades," adding, "despite the fact that the underlying causes of such increase are often attributed to a changing climate, scientific evidence points to increasing exposure and vulnerability as the main factors responsible for the increase in losses," citing the studies of Pielke and Landsea (1998), Crompton and McAneney (2008), Pielke *et al*. (2008), Barredo (2009, 2010), and Neumayer and Barthel (2011). Barredo *et al*. examined "the time history of insured losses from floods in Spain between 1971 and 2008," striving to see "whether any discernible residual signal remains after adjusting the data for the increase in the number and value of insured assets over this period of time."

The "most salient feature" of Barredo *et al*.'s findings, as they describe it, is "the absence of a significant positive trend in the adjusted insured flood losses in Spain," suggesting "the increasing trend in the original losses is explained by socio-economic factors, such as the increases in exposed insured properties, value of exposed assets and insurance penetration." They add "there is no residual signal that remains after adjusting for these factors," so "the analysis rules out a discernible influence of anthropogenic climate change on insured losses," which they say "is consistent with the lack of a positive trend in hydrologic floods in Spain in the last 40 years."

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7.5.3.5 Switzerland

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Switzerland.

Schmocker-Fackel and Naef (2010a) investigated how flooding in Switzerland may have responded to the post-Little Ice Age warming of the past century and a half, especially in light of the extreme flooding that occurred there in 1999, 2005, and 2007. They "analyzed streamflow data from 83 stations with a record length of up to 105 years, complemented with data from historical floods dating back to 1850." The two researchers found, "in Switzerland, periods with frequent floods have alternated with quieter periods during the last 150 years," and "since 1900, flood-rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa." They also note although "three of the four largest large-scale flood events in northern Switzerland have all occurred within the last ten years," "a similar accumulation of large floods has already been observed in the second half of the 19th century," and "studies about changes in precipitation frequencies in Switzerland come to similar conclusions," citing the work of Bader and Bantle (2004).

In a contemporaneous publication, Schmocker-Fackel and Naef (2010b) collected and analyzed historical flood data from 14 catchments in northern Switzerland. This second work revealed four periods of frequent flooding lasting between 30 and 100 years each: 1560–1590, 1740–1790, 1820–1940, and since 1970. Schmocker-Fackel and Naef report the first three periods of intervening low flood frequency (1500–1560, 1590–1740, and 1790–1810) were found to correspond to periods of low solar activity. However, they note, "after 1810 no relationship between solar activity and flood frequency was found, nor could a relationship be established between reconstructed North Atlantic Oscillation indices or reconstructed Swiss temperatures." In addition, they determined "the current period of increased flood frequencies has not yet exceeded those observed in the past." They also note "a comparison with the flood patterns of other European rivers suggests that flood frequencies are not in phase over Europe."

Schmocker-Fackel and Naef conclude "the current period with more floods in northern Switzerland, which started in the mid 1970s, might continue for some decades," even under conditions of "natural climatic variation."

Stewart *et al.* (2011) note "regional climate models project that future climate warming in Central Europe will bring more intense summer-autumn heavy precipitation and floods as the atmospheric concentration of water vapor increases and cyclones intensify," citing the studies of Arnell and Liu (2001), Christensen and Christensen (2003), and Kundzewicz *et al.* (2005). They derived "a complete record of paleofloods, regional glacier length changes (and associated climate phases) and regional glacier advances and retreats (and associated climate transitions) … from the varved sediments of Lake Silvaplana (ca. 1450 BC–AD 420; Upper Engadine, Switzerland)," while indicating "these records provide insight into the behavior of floods (i.e. frequency) under a wide range of climate conditions."

The five researchers report there was "an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June–July–August temperatures" and the frequency of flooding "was reduced during warm and/or dry climates." Reiterating that "the findings of this study suggest that the frequency of extreme summer–autumn precipitation events (i.e. flood events) and the associated atmospheric pattern in the Eastern Swiss Alps was not enhanced during warmer (or drier) periods," Stewart *et al*. acknowledge "evidence could not be found that summer–autumn floods would increase in the Eastern Swiss Alps in a warmer climate of the 21st century," in contrast to the projections of regional climate models that have suggested otherwise.

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7.5.3.6 Multiple Countries

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to multiple countries across Europe.

Starkel (2002) reviewed what is known about the relationship between extreme weather events and the thermal climate of Europe during the Holocene. This review clearly demonstrated more extreme fluvial activity was typically associated with *cooler* time intervals. In recovering from one such period (the Younger Dryas), for example, temperatures in Germany and Switzerland rose by 3–5°C over several decades; "this fast shift," in Starkel's words, "caused a rapid expansion of forest communities, [a] rise in the upper treeline and higher density of vegetation cover," which led to a "drastic" reduction in sediment delivery from slopes to river channels.

Mudelsee *et al*. (2003) analyzed historical documents from the eleventh century to 1850, plus subsequent water stage and daily runoff records from then until 2002, for two of the largest rivers in central Europe: the Elbe and Oder Rivers. For the prior 80 to 150 years, which the IPCC typically describes as a period of unprecedented global warming, they discovered "a decrease in winter flood occurrence in both rivers, while summer floods show[ed] no trend, consistent with trends in extreme precipitation occurrence."

Mudelsee *et al*. (2004) wrote "extreme river floods have had devastating effects in central Europe in recent years," citing as examples the Elbe flood of August 2002, which caused 36 deaths and inflicted damages totaling more than US $15 billion, and the Oder flood of July 1997, which caused 114 deaths and inflicted approximately US $5 billion in damages. They note concern had been expressed "in the Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change," wherein it was stated "current anthropogenic changes in atmospheric composition will add to this risk."

The four researchers reevaluated the quality of data and methods of reconstruction that had previously produced flood histories of the middle parts of the Elbe and Oder rivers back to AD 1021 and 1269, respectively. For both rivers, they found "no significant trends in summer flood risk in the twentieth century," but "significant downward trends in winter flood risk." The latter phenomenon—described as "a reduced winter flood risk during the instrumental period"—they specifically described as "a response to regional warming." Thus their study provided no support for the IPCC's concern that CO_2-induced warming would add to the risk of river flooding in Europe. If anything, their findings suggest just the opposite.

Based on flood loss information obtained from the Emergency Events Database and Natural Hazards Assessment Network, Barredo (2009) developed a 1970–2006 history of normalized monetary flood losses in Europe—including the member states of the European Union along with Norway, Switzerland, Croatia, and the former Yugoslav Republic of Macedonia—by calculating the value of losses that would have occurred if the floods of the past had taken place under the current socioeconomic conditions of the continent, while further removing inter-country price differences by adjusting the losses for purchasing power parities. This work revealed, in the analyst's words, "no evidence of a clear positive trend in normalized flood losses in Europe," and "changes in population, inflation and per capita real wealth are the main factors contributing to the increase of the original raw losses." After removing the influence of socioeconomic factors, the European Commission researcher states, "there remains no evident signal suggesting any influence of anthropogenic climate change on the trend of flood losses in Europe during the assessed period."

Buntgen *et al*. (2010) point out instrumental station measurements, which systematically cover only the past 100–150 years, "hinder any proper assessment of the statistical likelihood of return period, duration and magnitude of climatic extremes," stating "a palaeoclimatic perspective is therefore indispensable to place modern trends and events in a pre-industrial context (Battipaglia *et al*., 2010), to disentangle effects of human greenhouse gas emission from natural forcing and internal oscillation (Hegerl *et al*., 2011), and to constrain climate model simulations and feedbacks of the global carbon cycle back in time (Frank *et al*., 2010)." Buntgen *et al*. "introduce and analyze 11,873 annually resolved and absolutely dated ring width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period," and which "allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations."

The nine researchers state their data revealed "a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming." This finding, the authors write, "may question the common belief that frequency and severity of such events closely relates to climate mean states."

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7.5.3.7 Other European Countries

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to other countries in Europe not previously discussed in prior subsections of this topic.

7.5.3.7.1 Norway

Nesje *et al*. (2001) analyzed a sediment core from a lake in southern Norway in an attempt to determine the frequency and magnitude of prior floods in that region. The last thousand years of the record revealed "a period of little flood activity around the Medieval period (AD 1000–1400)," followed by a period of extensive flood activity associated with the "post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age.'" Thus this study suggests the post-Little Ice Age warming Earth has experienced for the last century or two—which could continue for some time to come—should be leading this portion of the planet into a period of less extensive flooding as opposed to the more extensive flooding typically predicted by climate models to occur in response to warming.

7.5.3.7.2 Finland

According to Korhonen and Kuusisto (2010), "annual mean temperatures in Finland increased by about 0.7°C during the 20th century," citing Jylha *et al.* (2004), while noting under such a warming regime, "both droughts and floods are expected to intensify." The two Finnish researchers analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland to 2004, using data supplied by the Finnish Environment Institute.

They found as "winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites." They further noted "the magnitudes of spring high flow have not changed." Low flows, by contrast, "have increased at about half of the unregulated sites due to an increase in both winter and summer discharges." They conclude, "statistically significant overall changes have not been observed in mean annual discharge." Thus, in contrast to typical global warming projections, at the high end where flooding may occur, there has been no change in the magnitude of flows. At the low end, where droughts may occur, there has been an increase in flow magnitude, which acts to prevent or leads to less frequent and/or less severe episodes of drought.

7.5.3.7.3 Slovakia

Stankoviansky (2003) employed topographical maps and aerial photographs, field geomorphic investigation, and the study of historical documents, including those from local municipal and church sources, to determine the spatial distribution of gully landforms and the temporal history of their creation in the Myjava Hill Land of Slovakia, situated in the western part of the country near its border with the Czech Republic. He found "the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s and the second roughly between the 1780s and 1840s." He determined these gullies were formed "during periods of extensive forest clearance and expansion of farmland," but "the triggering mechanism of gullying was extreme rainfalls during the Little Ice Age." He notes "the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age." Subsequently, from the mid-nineteenth century to the present, he reports "there has been a decrease in gully growth because of the afforestation of gullies and especially climatic improvements since the termination of the Little Ice Age."

7.5.3.7.4 Sweden

Lindstrom and Bergstrom (2004) analyzed runoff and flood data from more than 60 discharge stations throughout Sweden, some of which provided information stretching as far back in time as the early 1800s, when Sweden and the world were still experiencing the cold of the Little Ice Age. They discovered the last 20 years of the past century were indeed unusually wet, with a runoff anomaly of +8% compared with the century average. But they also found "the runoff in the 1920s was comparable to that of the two latest decades," and "the few observation series available from the 1800s show that the runoff was even higher than recently." In addition, they determined "flood peaks in old data [were] probably underestimated," which "makes it difficult to conclude that there has really been a significant increase in average flood levels." They also state "no increased frequency of floods with a return period of 10 years or more, could be determined."

Lindstrom and Bergstrom conclude conditions in Sweden "are consistent with results reported from nearby countries: e.g. Forland *et al.* (2000), Bering Ovesen *et al.* (2000), Klavins *et al.* (2002) and Hyvarinen (2003)," and "in general, it has been difficult to show any convincing evidence of an increasing magnitude of floods (e.g. Roald, 1999) in the near region, as is the case in other parts of the world (e.g. Robson *et al*., 1998; Lins and Slack, 1999; Douglas *et al*., 2000; McCabe and Wolock, 2002; Zhang *et al*., 2001)."

7.5.3.7.5 Poland

Cyberski *et al*. (2006) used documentary sources of information (written documents and "flood boards") to develop a reconstruction of winter flooding of the Vistula River in Poland back to AD 988. This work indicated, in their words, that winter floods "have exhibited a decreasing frequency of snowmelt and ice-jam floods in the warming climate over much of the Vistula basin." In addition, they report the work of Pfister (2005) indicates most of Central Europe also has become less drought-prone in winter during the twentieth century. It would appear twentieth century global warming has been accompanied by reductions in floods and droughts in much of Central Europe, just the opposite of model-based projections.

7.5.3.7.6 Italy

Diodato *et al*. (2008) undertook a detailed analysis of "the Calore River Basin (South Italy) erosive rainfall using data from 425-year-long series of both observations (1922–2004) and proxy-based reconstructions (1580–1921)." This work revealed pronounced interdecadal variations, "with multi-decadal erosivity reflecting the mixed population of thermo-convective and cyclonic rainstorms with large anomalies," and they note "the so-called Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall."

The three researchers conclude, "in recent years, climate change (generally assumed as synonymous with global warming) has become a global concern and is widely reported in the media." With respect to the concern that both droughts and floods will become both more frequent and more severe as the planet warms, they say their study indicates "climate in the Calore River Basin has been largely characterized by naturally occurring weather anomalies in past centuries (long before industrial CO_2 emissions), not only in recent years," and there has been a "relevant smoothing" of such events during the modern era.

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7.5.4 North America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to North America.

Lins and Slack (1999) analyzed secular streamflow trends in 395 parts of the United States derived from more than 1,500 individual stream gauges, some of which had continuous data stretching back to 1914. In the mean, they found "the conterminous U.S. is getting wetter, but less extreme." That is to say, as the near-surface air temperature of the planet gradually rose throughout the twentieth century, the United States became wetter in the mean but less variable at the extremes, which is where floods and droughts occur, leading to what could be considered the best of both worlds: more water with fewer floods.

Molnar and Ramirez (2001) conducted a detailed analysis of precipitation and streamflow trends for the period 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. At the annual timescale, they reported finding "a statistically significant increasing trend in precipitation," driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale, but monthly totals increased in low-flow months and decreased in high-flow months, once again reducing the likelihood of both floods and droughts.

Increased precipitation in a semiarid region would seem to be a good thing. Having most of the increase arrive in the moderate rainfall intensity range also would appear to be a good thing. Increasing streamflow in normally low-flow months sounds good too, as does decreasing streamflow in high-flow months. The changes in precipitation and streamflow observed by Molnar and Ramirez would appear to be highly desirable, leading to more water availability but a lowered probability of both floods and droughts.

Knox (2001) identified an analogous phenomenon in the more mesic Upper Mississippi River Valley. Since the 1940s and early 1950s, the magnitudes of the largest daily flows in this much wetter region have been decreasing while the magnitude of the average daily baseflow has been increasing, once again manifesting simultaneous trends towards both lessened flood and drought conditions.

Garbrecht and Rossel (2002) studied the nature of precipitation throughout the U.S. Great Plains over the period 1895–1999. For the central and southern Great Plains, the last two decades of this period were found to be the longest and wettest of the 105 years of record, due primarily to a reduction in the number of dry years and an increase in the number of wet years. Once again, however, the number of very wet years, which would be expected to produce flooding, "did not increase as much and even showed a decrease for many regions."

The northern and northwestern Great Plains experienced a precipitation increase near the end of Garbrecht and Rossel's 105-year record, but the increase was confined primarily to the final decade of the twentieth century. As they report, "fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions."

The last decade of the past century did produce significant floods, such as the 1997 flooding of the Red River of the North, which devastated Grand Forks, North Dakota as well as parts of Canada. As Haque (2000) reports, this flood was the largest in the Red River over the past century, but it was not the largest in historic times. In 1852, for example, there was a slightly larger Red River flood, and in 1826 there was a flood nearly 40% greater than that of 1997. The temperature of the globe was much colder at the times of these earlier catastrophic floods than it was in 1997, suggesting one cannot attribute the strength of the 1997 flood to the degree of warmth experienced that year or the preceding decade.

Olsen *et al*. (1999) report some upward trends in flood-flows have been found in certain places along the Mississippi and Missouri Rivers; there will always be exceptions to the general rule. At the same time, they note many of the observed upward trends were highly dependent upon the length of the data record and when the trends began and ended. Hence, they say these trends "were not necessarily there in the past and they may not be there tomorrow."

Pinter *et al*. (2008) also tested for long-term changes in flood magnitudes and frequencies in the Mississippi River system. They "constructed a hydrologic database consisting of data from 26 rated stations (with both stage and discharge measurements) and 40 stage-only stations." Then, to help "quantify changes in flood levels at each station in response to construction of wing dikes, bendway weirs, meander cutoffs, navigational dams, bridges, and other modifications," the researchers compiled a geospatial database consisting of "the locations, emplacement dates, and physical characteristics of over 15,000 structural features constructed along the study rivers over the past 100–150 years." Pinter *et al*. say "significant climate- and/or land use-driven increases in flow were detected," but "the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures, followed by progressive levee construction."

Pinter *et al*. write "the navigable rivers of the Mississippi system have been intensively engineered, and some of these modifications are associated with large decreases in the rivers' capacity to convey flood flows." It would appear man may indeed have been responsible for most of the enhanced flooding of the rivers of the Mississippi system over the past century or so, but not in the way suggested by the IPCC. The question that needs addressing by the region's inhabitants, therefore, has nothing to do with CO_2, but everything to do with how to "balance the local benefits of river engineering against the potential for large-scale flood magnification."

Similar findings have been reported for the Upper Midwest (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois) by Villarini *et al*. (2011), who "analyzed the annual maximum instantaneous flood peak distributions for 196 U.S. Geological Survey streamflow stations with a record of at least 75 years over the Midwest U.S." According to the four U.S. researchers, the majority of streamflow changes they observed were "associated with change-points (both in mean and variance) rather than monotonic trends," and they indicated "these non-stationarities are often associated with anthropogenic effects." But rather than associate the increases with anthropogenic CO_2 emissions, they cite such things as "changes in land use/land cover, changes in agricultural practice, and construction of dams and reservoirs" as the primary cause(s). "In agreement with previous studies (Olsen *et al*., 1999; Villarini *et al*., 2009)," they conclude "there is little indication that anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S." And as they make doubly clear in the abstract of their paper, "trend analyses do not suggest an increase in the flood peak distribution due to anthropogenic climate change."

Villarini and Smith (2010) "examined the distribution of flood peaks for the eastern United States using annual maximum flood peak records from 572 U.S. Geological Survey stream gaging stations with at least 75 years of observations." This work revealed, "in general, the largest flood magnitudes are concentrated in the mountainous central Appalachians and the smallest flood peaks are concentrated along the low-gradient Coastal Plain and in the northeastern United States." They also found "landfalling tropical cyclones play an important role in the mixture of flood generating mechanisms, with the frequency of tropical cyclone floods exhibiting large spatial heterogeneity over the region." They also note "warm season thunderstorm systems during the peak of the warm season and winter-spring extratropical systems contribute in complex fashion to the spatial mixture of flood frequency over the eastern United States."

Of even greater interest to the climate change debate, they found "only a small fraction of stations exhibited significant linear trends," and "for those stations with trends, there was a split between increasing and decreasing trends." They also note "no spatial structure was found for stations exhibiting trends." Thus, they conclude, "there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States."

Much the same was reported for Canada by Cunderlik and Ouarda (2009), who evaluated trends in the timing and magnitude of seasonal maximum flood events based on data obtained from 162 stations of the Reference Hydrometric Basin Network established by Environment Canada over the 30-year period 1974–2003. The Canadian researchers report finding "only 10% of the analyzed stations show significant trends in the timing of snowmelt floods during the last three decades (1974–2003)," and they say these results imply "the occurrence of snowmelt floods is shifting towards the earlier times of the year," as would be expected in a warming world. They note most of the identified trends "are only weakly or medium significant results" and "no significant trends were found in the timing of rainfall-dominated flood events."

With respect to flood magnitudes, the two scientists state the trends they observed "are much more pronounced than the trends in the timing of the floods," but most of these trends "had negative signs, suggesting that the magnitude of the annual maximum floods has been decreasing over the last three decades." In addition, they found "the level of significance was also higher in these trends compared to the level of significance of the trends in the timing of annual maximum floods."

A number of studies have examined floods over much longer intervals of time. Wolfe *et al*. (2005), for example, conducted a multiproxy hydroecological analysis of Spruce Island Lake (58°51'N, 111°29'W), a shallow, isolated, upland lake in a bedrock basin located in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta, Canada, in an attempt to assess the impacts of both natural variability and anthropogenic change on the hydroecology of the region over the past 300 years. Specifically, their research was designed to answer three questions: (1) Have hydroecological conditions in Spruce Island Lake since 1968 (the year in which river flow became regulated from hydroelectric power generation at the headwaters of the Peace River) varied beyond the range of natural variation of the past 300 years? (2) Is there evidence that flow regulation of the Peace River has caused significant changes in hydroecological conditions in Spruce Island Lake? (3) How is hydroecological variability at Spruce Island Lake related to natural climatic variability and Peace River flood history?

Wolfe *et al*.'s research revealed hydroecological conditions varied substantially over the past 300 years, especially in terms of multidecadal dry and wet periods. For question #1, the authors found hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with both "markedly wetter and drier conditions compared to recent decades" having occurred prior to the time of Peace River flow regulation. With respect to question #2, they note the current drying trend is not the product of Peace River flow regulation, but rather the product of an extended drying period initiated in the early to mid-1900s. Lastly, with respect to question #3, Wolfe *et al*. found the multi-proxy hydro-ecological variables they analyzed were well correlated with other reconstructed records of natural climate variability, indicating a likely climatic influence on Spruce Island Lake hydroecological conditions over the period of record.

Thus there is nothing unusual about recent trends in the hydroecology of the Spruce Island Lake region. Wet and dry conditions of today fall well within the range of natural variability and show no fingerprint of anthropogenic global warming. What is more, they even bear no fingerprint of anthropogenic flow control on the Peace River since 1968, demonstrating, in the words of the authors, that "profound changes in hydro-ecological conditions are clearly a natural feature of this ecosystem, independent of human influence or intervention."

Shapley *et al*. (2005) developed a 1,000-year hydroclimate reconstruction from local bur oak (*Quercus macrocarpa*) tree-ring records and lake sediment cores from the Waubay Lake complex located in eastern South Dakota. During the 1990s, broad areas of the U.S. Northern Great Plains experienced notable lake highstands. Waubay Lake, for example, rose by 5.7 meters and more than doubled in area from 1993 to 1999, severely flooding roads, farms, and towns and prompting the Federal Emergency Management Agency to declare the region a disaster area on 1 June 1998. Shapley *et al*. set out to determine the historical context of that 1990s lake-level rise.

The researchers found "prior to AD 1800, both lake highstands and droughts tended towards greater persistence than during the past two centuries," such that "neither generally low lake levels occurring since European settlement (but before the recent flooding) nor the post-1930s pattern of steadily increasing water availability and favorableness for tree growth are typical of the long-term record." In this particular part of the world, longer-lasting floods and droughts of equal or greater magnitude than those of modern times occurred repeatedly prior to 1800.

Fye *et al*. (2003) developed multicentury reconstructions of summer (June–August) Palmer Drought Severity Index over the continental United States from annual proxies of moisture status provided by 426 climatically sensitive tree-ring chronologies. They found the greatest twentieth century wetness anomaly across the United States was the 13-year pluvial that occurred in the early part of the century, when it was considerably colder than it is now. Fye *et al.*'s analysis also revealed the existence of a 16-year pluvial from 1825 to 1840 and a prolonged 21-year wet period from 1602 to 1622, both of which occurred during the Little Ice Age.

St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin to reconstruct annual precipitation in southern Manitoba since A.D. 1409." They found, "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement."

Ni *et al*. (2002) used tree-ring chronologies to develop a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico, USA. They found several wet periods comparable to the wet conditions seen in the early 1900s and post-1976 occurred in 1108–1120, 1195–1204, 1330–1345 (which they denote "the most persistent and extreme wet interval"), the 1610s, and the early 1800s. All of these wet periods are embedded in the long cold expanse of the Little Ice Age.

Ely (1997) wrote "paleoflood records from nineteen rivers in Arizona and southern Utah, including over 150 radiocarbon dates and evidence of over 250 flood deposits, were combined to identify regional variations in the frequency of extreme floods," and this information "was then compared with paleoclimatic data to determine how the temporal and spatial patterns in the occurrence of floods reflect the prevailing climate." The results of this comparison indicated "long-term variations in the frequency of extreme floods over the Holocene are related to changes in the climate and prevailing large-scale atmospheric circulation patterns that affect the conditions conducive to extreme flood-generating storms in each region." These changes, in Ely's view, "are very plausibly related to global-scale changes in the climate system."

With respect to the Colorado River watershed, for example, which integrates a large portion of the interior western United States, she writes "the largest floods tend to be from spring snowmelt after winters of heavy snow accumulation in the mountains of Utah, western Colorado, and northern New Mexico," such as occurred with the "cluster of floods from 5 to 3.6 ka," which occurred in conjunction with "glacial advances in mountain ranges throughout the western United States" during the "cool, wet period immediately following the warm mid-Holocene."

The frequency of extreme floods also increased during the early and middle portions of the first millennium AD, many of which coincided "with glacial advances and cool, moist conditions both in the western U.S. and globally." Then came a "sharp drop in the frequency of large floods in the southwest from AD 1100–1300," which corresponded, in her words, "to the widespread Medieval Warm Period, which was first noted in European historical records." With the advent of the Little Ice Age, there was another "substantial jump in the number of floods in the southwestern U.S.," which was "associated with a switch to glacial advances, high lake levels, and cooler, wetter conditions."

Distilling her findings to a single succinct statement, and speaking specifically of the southwestern United States, Ely writes, "global warm periods, such as the Medieval Warm Period, are times of dramatic decreases in the number of high-magnitude floods in this region."

Schimmelmann *et al*. (2003) analyzed gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, USA, which they accurately dated by varve-counting. They found six prominent flood events at approximately AD 212, 440, 603, 1029, 1418, and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200, and 1800. They further note "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells"; "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)"; and "the flood of ~AD 1418 occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al*., 1997; Meeker and Mayewski, 2002)." They hypothesize "solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years," and "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century." If such flooding occurs in the near future, there will be no need to suppose it came as a consequence of what the IPCC calls the unprecedented warming of the past century.

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of streamflow variability for this part of North America over the past 4,000 years. This work revealed the highest rates of stream discharge during this period occurred during the Little Ice Age, approximately 300–350 years ago, at which time grain sizes were about 2.5 standard deviations above the 4,000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, during the Medieval Warm Period, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean.

Carson *et al*. (2007) developed a Holocene history of flood magnitudes from reconstructed cross-sectional areas of abandoned channels and relationships relating channel cross-sections to flood magnitudes derived from modern stream gauge and channel records for the northern Uinta Mountains of northeastern Utah. Carson *et al*. report over the past 5,000 years the record of bankfull discharge "corresponds well with independent paleoclimate data for the Uinta Mountains," and "during this period, the magnitude of the modal flood is smaller than modern during warm dry intervals and greater than modern during cool wet intervals," noting most particularly "the decrease in flood magnitudes following 1000 cal yr B.P. corresponds to numerous local and regional records of warming during the Medieval Climatic Anomaly." The three largest negative departures from modern bankfull flood magnitudes (indicating greater than modern warmth) range approximately 15–22%, as best as can be determined from visual inspection of their plotted data, and they occur between about 750 and 600 cal yr B.P., as determined from radiocarbon dating of basal channel-fill sediments.

Carson *et al*.'s findings demonstrate the degree of natural variability in northeastern Utah flood magnitudes throughout the Holocene has been much larger (in both positive and negative directions) than what has been observed in modern times. Moreover, their work demonstrates the portion of the Medieval Warm Period between about AD 1250 and 1400 was likely significantly warmer than it is at present. Something other than high concentrations of atmospheric CO_2 was responsible for the region's warmth at that time, and thus one need not invoke today's much higher CO_2 concentrations as the reason for our actually lower current temperatures.

Brown *et al*. (1999) analyzed properties of cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow over the past 5,300 years. They found evidence of seven large megafloods, which they describe as "almost certainly larger than historical floods in the Mississippi watershed." They say these fluvial events were likely "episodes of multidecadal duration," five of which occurred during cold periods similar to the Little Ice Age.

Noren *et al*. (2002) employed several techniques to identify and date terrigenous in-wash layers found in sediment cores extracted from 13 small lakes distributed across a 20,000-km^2 region in Vermont and eastern New York that depict the frequency of storm-related floods. Their results indicate "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." Specifically, they found four major peaks in the data during this period, with the most recent upswing in storm-related floods beginning "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." In addition, they note several "independent records of storminess and flooding from around the North Atlantic show maxima that correspond to those that characterize our lake records [Brown *et al*., 1999; Knox, 1999; Lamb, 1979; Liu and Fearn, 2000; Zong and Tooley, 1999]."

Hirsch and Ryberg (2012) point out "one of the anticipated hydrological impacts of increases in greenhouse gas concentrations in the atmosphere is an increase in the magnitude of floods," citing Trenberth (1999), the IPCC (2007), and Gutowski *et al*. (2008). Working with the global mean carbon dioxide concentration (GMCO2) and a streamflow dataset consisting of long-term (85- to 127-year) annual flood series from 200 stream gauges deployed by the U.S. Geological Survey in basins with little or no reservoir storage or urban development (less than 150 persons per square kilometer in AD 2000) throughout the conterminous United States, which they divided into four large regions, Hirsch and Ryberg employed a stationary bootstrapping technique to determine whether the patterns of the statistical associations between the two parameters were significantly different from what would be expected under the null hypothesis that flood magnitudes are independent of GMCO2.

The two researchers report "in none of the four regions defined in this study is there strong statistical evidence for flood magnitudes increasing with increasing GMCO2." One region, the southwest, showed a statistically significant negative relationship between GMCO2 and flood magnitudes. Hirsch and Ryberg conclude "it may be that the greenhouse forcing is not yet sufficiently large to produce changes in flood behavior that rise above the 'noise' in the flood-producing processes."It could also mean the "anticipated hydrological impacts" envisioned by the IPCC and others are simply incorrect.

Taken together, the research described in this subsection suggest, if anything, that North American flooding tends to become less frequent and less severe when the planet warms, although there have been exceptions to this general rule. Although there could be exceptions to this rule in the future, it is more likely than not that any further warming of the globe would tend to further reduce both the frequency and severity of flooding in North America—just the opposite of what climate models suggest would occur.

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7.5.5 South America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to South America.

River flow records in southern South America, according to Mundo *et al.* (2012), “extend for only a few decades, hampering the detection of long-term, decadal to centennial-scale cycles and trends,” which are needed in order to ascertain the degree of validity of model-based claims for that part of the world.

To extend the streamflow history of Argentina’s Neuquen River—which Mundo *et al.* say is of “great importance for local and national socio-economic activities such as hydroelectric power generation, agriculture and tourism”—the authors employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of the river for each year of the 654-year period AD 1346–2000, using a nested principal component regression approach.

In terms of the frequency, intensity, and duration of droughts and pluvial events, the eight researchers determined “the 20th century contains some of the driest and wettest annual to decadal-scale events in the last 654 years.” They also report “longer and more severe events were recorded in previous centuries.”

Rein *et al.* (2004) derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima, Peru. The authors reported finding a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the late Medieval period. “Lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250,” they report, indicating a sustained period absent of large floods. They state "all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly." In addition, they note "this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain," citing 11 references.

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7.6 Precipitation

The IPCC and others claim global warming will cause greater variability in precipitation, frequently manifested in climate models as more frequent and heavier rainfall events. The IPCC has stated "in the near term, it is likely that the frequency and intensity of heavy precipitation events will increase at the global scale and at high latitudes" (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). The IPCC expects changes in average precipitation as well; some regions will increase, others will decrease, but on the whole, global precipitation is expected to increase.

General trends in precipitation are examined in Chapter 6 of this volume, where observational data indicate there is nothing unusual or unprecedented about recent precipitation events and trends in most regions, suggesting rising atmospheric CO_2 is having no measurable effect on precipitation totals. This section focuses on the variability or extremeness of precipitation, seeking to determine whether there is compelling evidence from historical observations that recent changes, if they are occurring, are the product of Earth's rising atmospheric CO_2 concentration.

As revealed in the subsections below, numerous studies suggest there is, in fact, no CO_2 influence on the variability or extremeness of precipitation. Moisture extremes much greater than those observed in the modern era have occurred throughout the historic past. Recent trends and events are neither unusual nor manmade; they are simply a normal part of Earth's natural climatic variability.

7.6.1 Africa

Nicholson and Yin (2001) describe climatic and hydrologic conditions in equatorial East Africa from the late 1700s to close to the present, based on histories of the levels of 10 major African lakes. They also use a water balance model to infer changes in rainfall associated with the different conditions, concentrating most heavily on Lake Victoria. This work reveals "two starkly contrasting climatic episodes." The first, which began sometime prior to 1800 and was characteristic of Little Ice Age conditions, was one of "drought and desiccation throughout Africa." This arid episode, which was most extreme during the 1820s and 1830s, was accompanied by extremely low lake levels. As the two researchers describe it, "Lake Naivash was reduced to a puddle ... Lake Chad was desiccated ... Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides ... Lake Rukwa [was] completely desiccated ... Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up." Throughout this period, they report, "intense droughts were ubiquitous." Some were "long and severe enough to force the migration of peoples and create warfare among various tribes."

As the Little Ice Age's grip on the world began to loosen in the mid to late 1800s, things began to improve for most of the continent. Nicholson and Yin report "semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests, ... the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region." Across the length of the northern Sahel, maps and geographical reports described the presence of "forests." As the nineteenth century came to an end and the twentieth century began, there was a slight lowering of lake levels, but nothing like what had occurred a century earlier (i.e., the precipitation variability was much reduced). In the latter half of the twentieth century, the levels of some of the lakes rivaled the high-stands characteristic of the years of transition to the Current Warm Period.

Nicholson (2001) reports the most significant climatic change in the more recent past has been "a long-term reduction in rainfall in the semi-arid regions of West Africa," which has been "on the order of 20 to 40% in parts of the Sahel." There have been, she states, "three decades of protracted aridity," and "nearly all of Africa has been affected ... particularly since the 1980s." She goes on to note "the rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented" and "a similar dry episode prevailed during most of the first half of the 19th century."

Nicholson says "the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of irreversible global change," because a longer historical perspective indicates an even longer period of similar dry conditions occurred between 1800 and 1850. This dry period occurred when Earth was still in the clutches of the Little Ice Age, a period of cold that is without precedent in at least the past 6,500 years, even in Africa (Lee-Thorp *et al*., 2001). There is therefore no reason to consider the most recent two- to three-decade Sahelian drought as unusual or the result of higher temperatures of that period.

Nguetsop *et al*. (2004) developed a high-resolution proxy record of West African precipitation based on analyses of diatoms recovered from a sediment core retrieved from Lake Ossa, West Cameroon, which they describe as "the first paleohydrological record for the last 5500 years in the equatorial near-coastal area, east of the Guinean Gulf." They report this record provides evidence for alternating periods of increasing and decreasing precipitation "at a millennial time scale for the last 5500 years," and they interpret this oscillatory behavior as being "a result of south/northward shifts of the Intertropical Convergence Zone," specifically noting "a southward shift of the ITCZ, combined with strengthened northern trade winds, was marked by low and high precipitation at the northern subtropics and the subequatorial zone, respectively," and "these events occurred in coincidence with cold spells in the northern Atlantic."

Therrell *et al*. (2006) developed "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This record revealed "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995)," and "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They report the year 1860, which exhibited the lowest reconstructed rainfall value during this period, was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, they report "a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era."

For a large part of central southern Africa, as well as other parts of the continent described above, it is clear twentieth century global warming has not resulted in an intensification of extreme dry and wet periods. If anything, just the opposite appears to have occurred.

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7.6.2 Asia

Pederson *et al.* (2001) developed tree-ring chronologies for northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Working with both standard deviations and 5-year intervals of extreme wet and dry periods, they found "variations over the recent period of instrumental data are not unusual relative to the prior record." They note, however, their reconstructions "appear to show more frequent extended wet periods in more recent decades," but this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." Spectral analysis of the data also revealed significant periodicities around 12 and 20–24 years, which they suggested may constitute "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Davi *et al.* (2006) used absolutely dated tree-ring-width chronologies obtained from five sampling sites in west-central Mongolia to derive individual precipitation histories, the longest of which stretches from 1340 to 2002, additionally developing a reconstruction of streamflow that extends from 1637 to 1997. They discovered there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," which for the region they studied covers the period from 1937 to 2003. In addition, they say their streamflow history indicates "the wettest 5-year period was 1764–68 and the driest period was 1854–58," and "the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83."

Liu *et al.* (2012) state "climate change is consistently associated with changes in a number of components of the hydrological cycle," including "precipitation patterns and intensity, and extreme weather events." Therefore, and in order to "provide advice for water resource management under climate change," they conducted a study of the subject in the Guangdong Province of Southern China, which occupies a land area of approximately 178,000 km^2 and has a population of just over 96 million people (as of 2009). The authors analyzed "trends of annual, seasonal and monthly precipitation in southern China (Guangdong Province) for the period 1956–2000 ... based on the data from 186 high-quality gauging stations," and they employed "statistical tests, including the Mann-Kendall rank test and wavelet analysis," to determine whether the precipitation series exhibited any regular trends or periodicities.

The four researchers report "annual precipitation has a slightly decreasing trend in central Guangdong and slight increasing trends in the eastern and western areas of the province," but "all the annual trends are not statistically significant at the 95% confidence level." They discovered "average precipitation increases in the dry season in central Guangdong, but decreases in the wet season," such that "precipitation becomes more evenly distributed within the year." They state "the results of wavelet analysis show prominent precipitation with periods ranging from 10 to 12 years in every sub-region in Guangdong Province." Comparing precipitation with the 11-year sunspot cycle, they find "the annual precipitation in every sub-region in Guangdong province correlates with Sunspot Number with a 3-year lag." Thus, rather than becoming more extreme in the face of 1956–2000 global warming, precipitation in China's Guangdong Province appears to have become both less extreme and less variable. The precipitation patterns that emerge upon proper analysis suggest the primary player in their determination is the Sun.

Ji *et al.* (2005) used reflectance spectroscopy on a sediment core taken from a lake in the northeastern part of the Qinghai-Tibetan Plateau to obtain a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. They found monsoonal moisture since the late glacial period had been subject to "continual and cyclic variations," among which was a "very abrupt onset and termination" of a 2,000-year dry spell that started about 4,200 years ago (yr BP) and ended around 2300 yr BP. Other variations included the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age (LIA), which lasted from 2100 yr BP to 1800 yr BP and 780 yr BP to 400 yr BP, respectively, while sandwiched between them was the warmer and wetter Medieval Warm Period, and preceding the DACP was the Roman Warm Period.

Time series analyses of the sediment record also revealed several statistically significant periodicities (123, 163, 200, and 293 years, all above the 95% level), with the 200-year cycle matching the de Vries or Suess solar cycle, implying changes in solar activity are important triggers for some of the recurring precipitation changes in that part of Asia. Ji *et al.*'s study shows large and abrupt fluctuations in the Asian monsoon have occurred numerous times and with great regularity throughout the Holocene, and the Sun played an important role in orchestrating those fluctuations.

Shao *et al.* (2005) used seven Qilian juniper ring-width chronologies from the northeastern part of the Qaidam Basin in the Tibetan Plateau to reconstruct a thousand-year history of annual precipitation. They discovered annual precipitation had fluctuated at various intervals and to various degrees throughout the past millennium. Wetter periods occurred between 1520 and 1633, as well as between 1933 and 2001, although precipitation has declined somewhat since the 1990s. Drier periods occurred between 1429 and 1519 and between 1634 and 1741. With respect to variability, the scientists report the magnitude of variation in annual precipitation was about 15 mm before 1430, increased to 30 mm between 1430 and 1850, and declined thereafter to the present. These findings together suggest the planet's current warmth is not unprecedented relative to that of the early part of the past millennium, or unprecedented warming need not lead to unprecedented precipitation or unprecedented precipitation variability, or both. This study does not provide support for the contention that global warming leads to greater and more frequent precipitation extremes.

Zhang *et al.* (2007) developed flood and drought histories of the past thousand years in China's Yangtze Delta "from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," upon which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." In comparing their findings with two one-thousand-year temperature histories from the region, the authors report "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region." In addition, during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred" in the flood/drought series.

In contrast, Zhang *et al*. report during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region." These findings once again illustrate warmer climates tend to be less variable than colder ones.

Touchan *et al*. (2005) developed summer (May-August) precipitation reconstructions for several parts of the eastern Mediterranean region (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back in time from 115 to 600 years. Over the latter period of time, they found May–August precipitation varied on multiannual and decadal timescales, but on the whole there were no long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods: 1601–1605 and 1751–1755. In addition, both extremely strong and weak precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930. This study thus also demonstrates there was nothing unusual or unprecedented about late-twentieth century precipitation events in the eastern Mediterranean part of Asia that would suggest a CO_2 influence. If anything, as this region transited from the record cold of the Little Ice Age to the peak warmth of the Current Warm Period, May–August precipitation became less variable in the face of rising temperatures.

Kripalani and Kulkarni (2001) studied seasonal summer monsoon (June–September) rainfall data from 120 east Asia stations for the period 1881–1998. A series of statistical tests they applied to these data revealed the presence of short-term variability in rainfall amounts on decadal and longer time scales, the longer "epochs" of which were found to last for about three decades over China and India and for approximately five decades over Japan. No long-term trends were detected. With respect to the decadal variability found in the record, the two researchers say it "appears to be just a part of natural climate variations."

Kishtawal *et al*. (2010) studied the Indian subcontinent (8.2°N to 35.35°N, 68.5°E to 97°E) to assess the impacts of urbanization on the region's rainfall characteristics during the Indian summer monsoon by analyzing *in situ* and satellite-based precipitation and population datasets. The five researchers found "a significantly increasing trend in the frequency of heavy rainfall climatology over urban regions of India during the monsoon season," adding "urban regions experience less occurrences of light rainfall and significantly higher occurrences of intense precipitation compared to non-urban regions."

What is the significance of these findings? In their book *Dire Predictions: Understanding Global Warming*, Mann and Kump (2008) note most climate model simulations of global warming indicate "increases are to be expected in the frequency of very intense rainfall events." Throughout most of the world, however, and as seen in the studies reviewed in this section, that expectation has not been fulfilled. Where increasing frequency of intense rainfall events has been observed in some studies, the findings of Kishtawal *et al*. and the papers they cite suggest urbanization may have been the cause. Moreover, the work of Hossain *et al*. (2009) suggests the proliferation of large dams also may be causing such events to occur. The work reviewed here suggests the only effect CO_2-induced global warming may be having on precipitation variability in Asia is to make it less rather than more variable.

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7.6.3 Europe

Alexandrov *et al*. (2004) analyzed various characteristics of climate in Bulgaria during the twentieth century by applying Meteo-France homogenization procedures to many raw datasets of the country, which procedures included, in their words, “control of monthly data of precipitation and average air temperature from selected weather stations in Bulgaria; detection of breaks and outliers within the collected and controlled time series; correction of the climate long-term series according to the defined breaks and outliers in order to obtain homogenized climate series.” They found “no significant warming trend during the last century in Bulgaria in spite of the slight increase of average air temperature during the last two decades.” They also note “a decreasing trend in annual and especially summer precipitation from the end of the 1970s was found,” and “variations of annual precipitation in Bulgaria showed an overall decrease.” Thus, as Bulgaria experienced a slight increase in average air temperature over the past two decades, the variability of annual precipitation decreased.

Ntegeka and Willems (2008) write “long-term temporal analysis of trends and cycles is crucial in understanding the natural variability within the climate system.” They performed “an empirical statistical analysis of trends in rainfall extremes ... based on the long-term high-frequency homogeneous rainfall series at the climatological station of the Royal Meteorological Institute of Belgium at Uccle.” This series was recorded by “the same measuring instrument at the same location since 1898 and processed with identical quality since that time,” and it was done at a measuring frequency of ten minutes, yielding more than 107 years of continuous data.

The Belgian researchers report "significant deviations in rainfall quantiles were found, which persisted for periods of 10 to 15 years," such that "in the winter and summer seasons, high extremes were clustered in the 1910s–1920s, the 1960s and recently in the 1990s." "This temporal clustering," the authors conclude, "highlights the difficulty of attributing 'change' in climate series to anthropogenically induced global warming," and they state "no strong conclusions can be drawn on the evidence of the climate change effect in the historical rainfall series."

Bohm (2012) notes "South Central Europe is among the spatially densest regions in terms of early instrumental climate data," citing Auer *et al.* (2007). He states this allows for successfully testing for homogeneity and developing "a larger number of very long instrumental climate time series at monthly resolution than elsewhere," which he thus proceeds to do. He notes the resulting long time series subset of the greater alpine region provides great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the "anthropogenic climate" of the past three decades. He reports "the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year 'normal periods' from 1771–1800 to 1981–2010."

Bohm concludes "the overwhelming majority of seasonal and annual sub-regional variability trends is not significant." In the case of precipitation, he writes, "there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period," and in the case of temperature he reports "most of the variability trends are insignificantly decreasing." In a "special analysis" of the recent 1981–2010 period that may be considered the first "normal period" under dominant greenhouse-gas-forcing, he finds all extremes "remaining well within the range of the preceding ones under mainly natural forcing." He notes "in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable."

Bohm, an Austrian researcher at the Central Institute for Meteorology and Geodynamics in Vienna, concludes there is "clear evidence that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period."

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7.6.4 North America

Cronin *et al.* (2000) studied salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United Sates, in an effort to determine precipitation variability in the surrounding watershed over the prior millennium. They discovered a high degree of decadal and multidecadal variability in moisture conditions over the 1,000-year period, with regional precipitation totals fluctuating by between 25% and 30%, often in extremely rapid shifts occurring over about a decade. They also determined precipitation was generally greater over the past two centuries than over the eight previous centuries, with the exception of a portion of the Medieval Warm Period (AD 1250–1350) when the climate was extremely wet. In addition, they found the region surrounding Chesapeake Bay had experienced several "megadroughts" lasting 60–70 years, some of which the researchers say "were more severe than twentieth century droughts."

Across the continent, Haston and Michaelsen (1997) developed a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies. Their work revealed "region-wide precipitation during the last 100 years has been unusually high and less variable compared to other periods in the past."

Watanabe *et al*. (2001) analyzed delta $^{18}O/^{16}O$ and Mg/Ca ratios in cores obtained from a coral in the Caribbean Sea to examine seasonal variability in sea surface temperature and salinity during the Little Ice Age. They found sea surface temperatures during this period were about 2°C colder than they are currently, and sea surface salinity exhibited greater variability than it does now, indicating during the Little Ice Age "wet and dry seasons were more pronounced."

Zhang *et al*. (2001) analyzed the spatial and temporal characteristics of extreme precipitation events for the period 1900–1998 in Canada, using what they describe as "the most homogeneous long-term dataset currently available for Canadian daily precipitation." The evidence indicated decadal-scale variability was a dominant feature of both the frequency and intensity of extreme precipitation events, but it provided "no evidence of any significant long-term changes" in these indices during the twentieth century. The authors' analysis of precipitation totals (extreme and non-extreme) revealed a slightly increasing trend across Canada during the period of study, but it was found to be due to increases in the number of non-heavy precipitation events. Consequently, the researchers conclude "increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada."

Tian *et al*. (2006) derived a high-resolution $\delta^{18}O$ record of endogenic calcite obtained from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. They found "the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods." Most striking, they found "drought variability was anomalously low during the 20th century"—so low that "~90% of the variability values during the last 3100 years were greater than the 20th-century average."

Gray *et al*. (2004) used cores extracted from 107 piñon pines at four different sites in the Uinta Basin Watershed of northeastern Utah to develop a proxy record of annual (June to June) precipitation spanning the period AD 1226–2001. They report "single-year dry events before the instrumental period tended to be more severe than those after 1900," and decadal-scale dry events were longer and more severe prior to 1900 as well. They note "dry events in the late 13th, 16th, and 18th centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900." At the other end of the spectrum, they report the twentieth century contained two of the strongest wet intervals (1938–1952 and 1965–1987), representing the seventh and second most intense wet regimes, respectively, of the record.

Rasmussen *et al*. (2006) earlier had demonstrated "speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004)." In their present work, they continued this tack, concentrating on "two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1) in the Guadalupe Mountains."

The three researchers report "both records, BC2 and HC1, suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record." They also note the time interval of AD 900–1300 coincides with the well-known Medieval Warm Period and "shows dampened precipitation variability and overall drier conditions" "consistent with the idea of more frequent La Niña events and/or negative PDO phases causing elevated aridity in the region during this time." They say the preceding and following colder centuries "show increased precipitation variability ... coinciding with increased El Niño flooding events."

Clearly, moisture extremes in North America much greater than those observed in the modern era have occurred. Recent trends are neither unusual nor manmade; they are simply a normal part of Earth's natural climatic variability. North America is like Africa, Asia, and Europe: Precipitation variability in the Current Warm Period is no greater than what was experienced in earlier times.

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7.7 Storms

Among the highly publicized changes in weather phenomena predicted to attend CO_2-induced global warming are increases in the frequency and severity of various types of storms. Storms are a concern for the residents of any coastal city, as high winds, water surges, and high-energy waves can cause damage via flooding and erosion. It is therefore important to examine the historical records of storms for trends, to see if the so-named unprecedented rise in atmospheric CO_2 and temperature of the late twentieth and early twenty-first century has had any measurable effect on such storms.

Section 7.7 begins with an analysis of all types of storms by region (Sections 7.7.1.1 through 7.7.1.5), followed by a review of a specific type of storm (Dust Storms, Section 7.7.2) and three phenomena often associated with extreme storms (Hail, Section 7.7.3; Tornadoes, Section 7.7.4; and Wind, Section 7.7.5).

7.7.1 Regional Trends

For the globe as a whole, in its most recent *Assessment Report* the IPCC states "over the last century there is low confidence of a clear trend in storminess due to inconsistencies between studies or lack of long-term data in some parts of the world (particularly in the Southern Hemisphere)," adding "a reduction in the occurrence of Northern Hemisphere extratropical storms is likely, although, the most intense storms reaching Europe will likely increase in the strength" (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

The subsections of Section 7.7.1 examine what scientists have learned empirically about historic storm trends in an effort to understand how their past behavior has changed in relation to past temperatures. The results of that examination indicate storm frequency and intensity will not increase as a result of global warming.

7.7.1.1 Australia/New Zealand

De Lange and Gibb (2000) analyzed trends in sea-level data from several tide gauges located within Tauranga Harbor, New Zealand over the period 1960–1998. In an examination of seasonal, interannual, and decadal distributions of storm surge data, the two researchers identified a considerable decline in the annual number of storm surge events in the latter half of the nearly four-decade-long record. A similar trend also was noted in the magnitude of storm surges; and maximum water levels, including tides, also declined over the past two decades. Additionally, the authors found decadal variations in the data were linked to both the Interdecadal Pacific Oscillation (IPO) and the El Niño/Southern Oscillation (ENSO), such that La Niña events were associated with more storm surge days than El Niño events. Wavelet analyses of annual storm surge frequency data suggested before 1978 the frequency "was enhanced by the IPO, and subsequently it has been attenuated."

Similar findings were reported a decade later by Page *et al.* (2010) who, working with sediment cores extracted from Lake Tutira on the eastern end of New Zealand's North Island, developed a much longer 7,200-year history of the frequency and magnitude of storm activity, based on analyses of sediment grain size, diatom, pollen, and spore types and concentrations, carbon and nitrogen concentrations, and tephra and radiocarbon dating.

The ten New Zealanders plus one U.S. researcher report "the average frequency of all storm layers is one in five years," but "for storm layers ≥ 1.0 cm thick, the average frequency is every 53 years." Over the course of their record, they state, "there are 25 periods with an increased frequency of large storms," the onset and cessation of which "was usually abrupt, occurring on an inter-annual to decadal scale." They also note the duration of these stormy periods "ranged mainly from several decades to a century," but "a few were up to several centuries long," and "intervals between stormy periods range from about thirty years to a century." In addition, they find millennial-scale cooling periods tend to "coincide with periods of increased storminess in the Tutira record, while warmer events match less stormy periods."

Page *et al.* comment there is growing concern, driven by climate models, that global warming may cause abrupt changes in various short-term meteorological phenomena, "when either rapid or gradual forces on components of the Earth system exceed a threshold or tipping point." Their research shows the sudden occurrence of a string of years, or even decades, of unusually large storms is something that can happen at almost any time on its own, or at least without being driven by human activities such as the burning of fossil fuels.

Hayne and Chappell (2001) studied a series of storm ridges deposited over the past 5,000 years at Curacoa Island on the central Queensland shelf (18°40'S; 146°33'E), Australia, to create a history of major cyclonic events that have affected the area. They find "cyclone frequency was statistically constant over the last 5,000 years" and report "no indication that cyclones have changed in intensity." They also note isotopic and trace element evidence from ancient corals indicate sea surface temperatures were about 1°C warmer about 5,000 years ago, and pollen spectra from lake sediments suggest rainfall at that time was about 20% higher than today. These results clearly indicate, at least for this location, that cyclone frequency and intensity do not respond to changes in temperature as climate models have predicted.

Alexander *et al.* (2011) point out "understanding the long-term variability of storm activity would give a much better perspective on how unusual recent climate variations have been." They note "for southeast and eastern Australia some studies have been able to assess measures of storm activity over longer periods back to the 19th century (e.g., Alexander and Power, 2009; Rakich *et al.*, 2008), finding either a decline in the number of storms or reduction in the strength of zonal geostrophic wind flow," although these studies "were limited to the analysis of only one or two locations."

The four researchers analyzed storminess across southeast Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century, finding "strong evidence for a significant reduction in intense wind events across SE Australia over the past century." They note "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease," while "in terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Yu *et al.* (2012) write "strong storms including cyclones, hurricanes, typhoons and strong wind events have catastrophic impacts on coral reefs worldwide," noting "Yu *et al.* (2004) suggested that the surface ages of well-preserved transported coral blocks could indicate the ages of past storm occurrences." This inference, they state, "was further confirmed by the analysis of sedimentation rates and grain sizes of lagoon sediments from the same reef (Yu *et al*., 2006; Yu *et al*., 2009)."

Yu *et al.* (2012) sampled 102 individual coral colonies (coral blocks) and four reef blocks they found distributed across the northern reef flat of Heron Reef, precisely dating them via the thermal ionization mass spectrometry (TIMS) U-series method, to explore their utility as indicators of historical storm activities around the southern end of the Great Barrier Reef, an area frequently visited by cyclones and storms, as noted by Done (1993) and Puotinen (2004). Based on the age distribution and relative probability frequency analysis of the dated coral and reef blocks, the seven scientists determined "there were eight relatively stormy periods since AD 1900, i.e., 1904–1909, 1914–1916, 1935–1941, 1945–1960, 1965–1967, 1976–1977, 1983–1988 and 2001–2007." Their yearly plot of the data clearly shows the very center of the twentieth century (1935–1965) to have been that century's most sustained stormy period in the vicinity of Heron Reef.

Li *et al.* (2011), citing "unprecedented public concern" with respect to the impacts of climate change, set out to examine the variability and trends of storminess for the Perth, Australia metropolitan coast. They conducted an extensive set of analyses using observations of wave, wind, air pressure, and water level over the period 1994–2008. The results of their analysis, in their view, would serve "to validate or invalidate the climate change hypothesis" that rising CO_2 concentrations are increasing the frequency and severity of storms.

As shown in Figure 7.7.1.1.1, all storm indices showed significant interannual variability over the period of record, but "no evidence of increasing (decreasing) trends in extreme storm power was identified to validate the wave climate change hypotheses for the Perth region."

In spite of what the Intergovernmental Panel on Climate Change has characterized as unprecedented global warming over the past two decades, Perth (Australia) has not experienced an increase in storm frequency or intensity. The studies cited above give little reason to believe CO_2-induced global warming will lead to increases in the frequency and magnitude of storms. Such claims are ungrounded in the peer-reviewed literature and have no basis in real-world observations.

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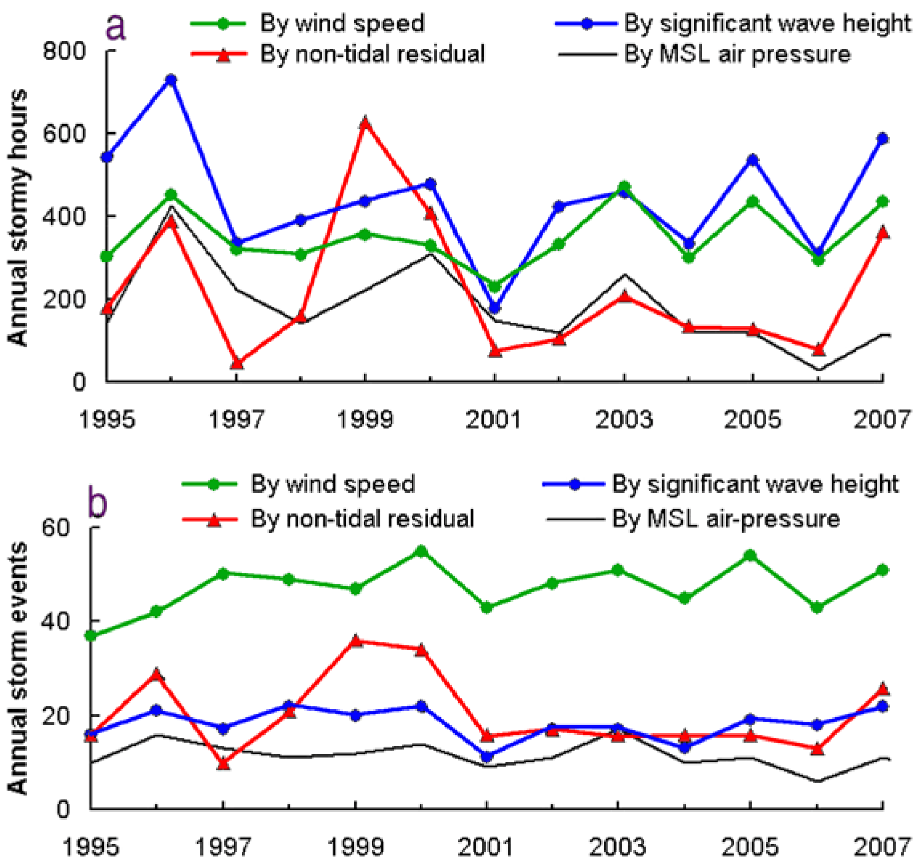

Figure 7.7.1.1.1. Annual storm trends for Perth, Australia defined by (a) stormy hours and (b) number of storm events, as determined by wind speed, significant wave height, non-tidal residual water level, and mean sea level pressure. Adapted from Li, F., Roncevich, L., Bicknell, C., Lowry, R., and Ilich, K. 2011. Interannual variability and trends of storminess, Perth, 1994–2008. *Journal of Coastal Research* **27**: 738–745.

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7.7.1.2 Europe

7.7.1.2.1 France

With respect to extreme weather events, Dezileau *et al*. (2011) write the major question of the day is, "are they linked to global warming or are they part of natural climate variability?" They say "it is essential to place such events in a broader context of time, and trace the history of climate changes over several centuries," because "these extreme events are inherently rare and therefore difficult to observe in the period of a human life."

Dezileau *et al*., nine researchers from France, analyzed regional historical archives and sediment cores extracted from two Gulf of Aigues-Mortes lagoons in the northwestern part of the occidental Mediterranean Sea for bio- and geo-indicators of past storm activities there, assessing "the frequency and intensity of [extreme] events during the last 1500 years" as well as "links between past climatic conditions and storm activities." The analysis showed evidence of four "catastrophic storms of category 3 intensity or more," which occurred at approximately AD 455, 1742, 1848, and 1893. "Taking into account text description of the 1742 storm," they conclude it was "of category more than 4 in intensity," and all four of the storms "can be called superstorms."

Dezileau *et al*. make a point of noting "the apparent increase in intense storms around 250 years ago lasts to about AD 1900," whereupon "intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD)." They add, "interestingly, the two periods of most frequent superstorm strikes in the Aigues-Mortes Gulf (AD 455 and 1700–1900) coincide with two of the coldest periods in Europe during the late Holocene (Bond cycle 1 and the latter half of the Little Ice Age.)" The authors suggest "extreme storm events are associated with a large cooling of Europe," and they calculate the risk of such storms occurring during that cold period "was higher than today by a factor of 10," noting "if this regime came back today, the implications would be dramatic."

Clarke *et al*. (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, finding dune formation was generally most common during cooler climatic intervals. In the most recent of these cold periods, the authors note there is voluminous historical evidence of many severe North Atlantic wind storms in which the southward spread of sea ice and polar water likely created "an increased thermal gradient between 50°N and 65°N which intensified storm activity in the North Atlantic ... which may well have mobilized sand inland from the coast." In addition, they note sand-drift episodes across Europe "show synchroneity with sand invasion in the Aquitaine region of southwest France, implying a regional response to increased storminess." Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Working with historical accounts as well as "sedimentology, granulometry and faunistic data" obtained from two cores of the Pierre Blanche lagoon just south of Montpellier, France, Sabatier *et al.* (2008) found evidence of "washover events" that allowed them "to identify the strongest storms in the Mediterranean area" over the past four centuries. The eight researchers found "evidence of three main storms," which they identified as occurring in 1742, 1839, and 1893, all of which were deemed to have been much stronger than any of the twentieth century. A storm that occurred in 1982, which they describe as having been "the most recent catastrophic event," was not even "registered" in the lagoon sediment cores. Such a decline in the occurrence of "superstorms" in the Mediterranean area is a significant observation running counter to the model-based claim that global warming intensifies storms and brings more of them.

Sorrel *et al*. (2009) say studies indicate "estuarine systems are particularly sensitive to changing hydrological conditions," and one of the major purposes of examining them has been to determine "the effects of past centennial- to millennial-scale natural climatic fluctuations" in order to "better predict the impact of present-day and forthcoming climatic changes (and/or anthropogenic activities) on estuary infill." Of "crucial impact," in their estimation, "is the impact of storminess within warmer and colder periods on sedimentary patterns through the climatic regulation of (i) coastal wave hydrodynamics and (ii) continental inputs from the Seine river catchment area [in the case of their specific study] during the late Holocene."

Sorrel *et al*. linked high-resolution sediment and rock properties of materials found in cores collected from the Seine estuary in northwest France to climatic conditions of the past few thousand years. The five French researchers found "increased removal and transport of estuarine sediments occurred when winter storm activity greatly intensified over northwestern France," and they report on "four prominent centennial-scale periods of stronger storminess, occurring with a pacing of ~1500 years," which they say are "likely to be related to the last four [of] Bond's [1997, 2001] Holocene cold events," the most recent of which was the Little Ice Age, when Sorrel *et al.* say tidal and open marine hydrodynamics exerted "primary control on the sedimentary evolution of the system during 1200–2003 AD." In contrast, they found "the preservation of sedimentary successions in the outer Seine estuary was maximal during ca. 800–1200 AD," which they identify as the Medieval Warm Period, when they say "sediment reworking by waves was considerably reduced."

Sorrel *et al*. (2010) conducted a similar analysis for the macrotidal Bay of Vilaine (47°20'–47°35'N, 2°50'–2°30'W). Their results indicated "the late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives," where the authors found "an increase in the contribution of riverine inputs occurred during the MWP [Medieval Warm Period]" at "times of strong fluvial influences in the estuary during ca. 880–1050 AD." They also report "preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal," in accordance with the findings of Proctor *et al.* (2000) and Meeker and Mayewski (2002). Furthermore, they state the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon *et al*. (2004) and Billeaud *et al.* (2005). They note, "all sedimentary records from the French and Spanish Atlantic coasts" suggest "the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development," adding "milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths."

Sorrell *et al.* (2010) also note the upper successions of the sediment cores "mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals," while observing "this shift most probably documents the transition from the MWP to the Little Ice Age," which led to the "increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and

Rendell, 2009)" associated with "the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard *et al*., 2007; Clemmensen *et al*., 2007, 2009; Matthews and Briffa, 2005), France (Meurisse *et al*., 2005), Netherlands (Jelgersma *et al*., 1995) and Scotland (Dawson *et al*., 2004)." In what they call an even "wider perspective," they note the Medieval Warm Period "is recognized as the warmest period of the last two millennia (Mayewski *et al*., 2004; Moberg *et al*., 2005)."

The French scientists conclude "the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD," implying "climatic conditions were probably mild enough to prevent coastal erosion in northwestern France."

Pirazzoli (2000) analyzed tide-gauge, wind, and atmospheric pressure data over the period 1951–1997 for the northern portion of the Atlantic coast of France. The author notes atmospheric depressions (storms) and strong surge winds "are becoming less frequent" in this region and "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding" over the period of study. Such findings should be "reassuring," Pirazzoli notes, especially for those concerned about coastal flooding.

The studies described above suggest there has been no significant increase in the frequency or intensity of stormy weather in France as Earth recovered from the global chill of the Little Ice Age. Storminess in most other parts of the planet also decreased over this period, as described in other subsections, suggesting there is no real-world, data-driven reason to believe storms would get any worse or become more frequent if Earth were to warm somewhat more in the future.

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7.7.1.2.2 United Kingdom

Allan *et al*. (2009) point out an analysis of a 47-year storm database by Alexander *et al*. (2005) "showed an increase in the number of severe storms in the 1990s in the United Kingdom," but "it was not possible to say with any certainty that this was either indicative of climatic change or unusual unless it was seen in a longer-term context." Allan *et al*. extended the database of Alexander *et al*. back to 1920, almost doubling the length of the record, after which they reanalyzed the expanded dataset for the periods of boreal autumn (October, November, December) and winter (January, February, March). They determined both databases exhibited peaks in storminess in the 1920s and 1990s, with boreal autumn storms being more numerous in the 1920s and winter storms being more numerous in the 1990s. The total storm numbers for each decade are plotted in Figure 7.7.1.2.2.1 As can be seen there, both the beginning and end decades of the record experienced nearly identical numbers of storms, demonstrating the increasingly greater number of extreme storms affecting the British Isles from the 1960s through the 1990s likely was not related to the global warming of that period.

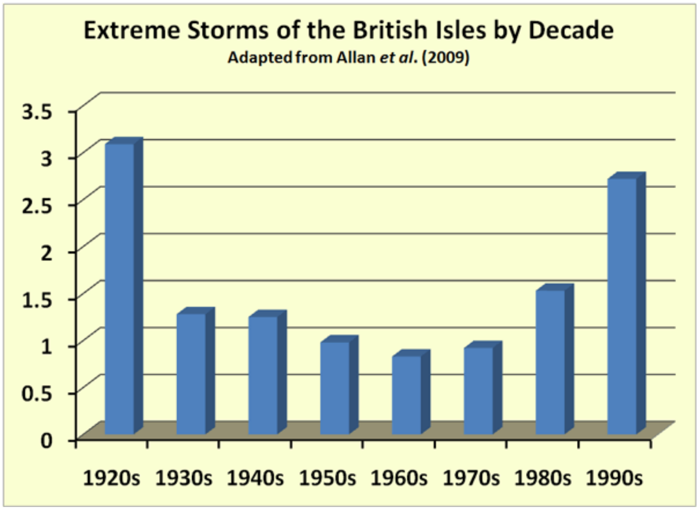

Figure 7.7.1.2.2.1. Number of extreme storms impacting the British Isles in each of eight decadal periods. Created from results reported by Allan, R., Tett, S., and Alexander, L. 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**: 357–371.

Dawson *et al*. (2002) searched daily meteorological records from northern and northwestern Scotland—Stornoway (Outer Hebrides), Lerwick (Shetland Islands), Wick (Caithness), and Fair Isle (west of the Shetland Islands)—for data pertaining to gale-force winds over the period 1876–1996, which they used to construct a history of storminess for that period. Although North Atlantic storminess and associated wave heights were found to have increased over the prior two decades, storminess in the North Atlantic region "was considerably more severe during parts of the nineteenth century than in recent decades." In addition, whereas the modern increase in storminess appeared to be associated with a spate of substantial positive values of the North

Atlantic Oscillation (NAO) index, Dawson *et al.* state "this was not the case during the period of exceptional storminess at the close of the nineteenth century." During that earlier period, the conditions that fostered modern storminess were apparently overpowered by something even more potent; i.e., cold temperatures, which the authors say led to an expansion of sea ice in the Greenland Sea that expanded and intensified the Greenland anticyclone, which in turn led to the North Atlantic cyclone track being displaced farther south. Additional support for this view is provided by the hypothesis of Clarke *et al.* (2002), who postulated that a southward spread of sea ice and polar water results in an increased thermal gradient between 50°N and 65°N that intensifies storm activity in the North Atlantic and supports dune formation in the Aquitaine region of southwest France.

These studies suggest the increased storminess and wave heights observed in the European sector of the North Atlantic Ocean over the past two decades are not the result of global warming, but rather are associated with the most recent periodic increase in the NAO index. A longer historical perspective reveals North Atlantic storminess was even more severe than it is now during the latter part of the nineteenth century, when it was significantly colder than it is now. The storminess of that much colder period was so great it was actually decoupled from the NAO index. Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Tide-gauge data also have been utilized as proxies for storm activity in England. Based on high-water measurements made at the Liverpool waterfront over the period 1768–1999, Woodworth and Blackman (2002) found the annual maximum surge-at-high-water declined at a rate of 0.11 ± 0.04 meters per century, suggesting the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (colder Little Ice Age) than the latter part (Current Warm Period).

Focusing on a well-studied and data-rich 16-km-long section of the Sefton coastline of northwest England, Esteves *et al.* (2011) used the longest available measured datasets from the eastern Irish Sea and beyond—including tide levels, surge heights, wind speeds, and wave heights—in a search for evidence of long-term changes in the metocean climate. They analyzed data defining the rate of change in shoreline position at the study site derived from a range of historical maps and aerial photographs for the period 1894–2005, with the primary aim of assessing "whether temporal changes in the rates and magnitudes of coastal erosion can be attributed to the observed trends in metocean data, and if these trends can, in turn, be associated with climate change."

According to the three UK researchers, their results "show no evidence of enhanced storminess or increases in surge heights or extreme water levels," and "the evolution of the coastline analyzed at various temporal scales shows no strong connection with metocean trends." With the exception of mean monthly wind speed (which trended slightly upwards at one site and slightly downwards at another), the authors report the available metocean data "do not indicate any statistically significant changes outside seasonal and decadal cycles."

Dawson *et al.* (2004a) examined the sedimentary characteristics of a series of Late Holocene coastal windstorm deposits found on the Scottish Outer Hebrides, an island chain that extends across the latitudinal range 56–58°N. These deposits form part of the landward edges of coastal sand accumulations that are intercalated with peat, the radiocarbon dating of which was used to construct a local chronology of the windstorms. This work revealed "the majority of the sand units were produced during episodes of climate deterioration both prior to and after the well-known period of Medieval warmth." The researchers also say "the episodes of sand blow indicated by the deposits may reflect periods of increased cyclogenesis in the Atlantic associated with increased sea ice cover and an increase in the thermal gradient across the North Atlantic region." In addition, they report "dated inferred sand drift episodes across Europe show synchroneity with increased sand mobilization in SW France, NE England, SW Ireland and the Outer Hebrides, implying a regional response to storminess with increased sand invasion during the cool periods of the Little Ice Age," citing the corroborative studies of Lamb (1995), Wintle *et al.* (1998), Gilbertson *et al.* (1999), and Wilson *et al.* (2001).

Dawson *et al.* (2004b) examined 120- to 225-year records of gale-days per year from five locations across Scotland, northwest Ireland, and Iceland, which they compared with a much longer 2,000-year record for the same general region. They found four of the five century-scale records showed a greater frequency of storminess in the cooler 1800s and early 1900s than throughout the remainder of the warmer twentieth century. "Considered over the last ca. 2000 years," they report, "it would appear that winter storminess and climate-driven coastal erosion was at a minimum during the Medieval Warm Period," just the opposite of what climate models typically predict; i.e., more storminess with warmer temperatures.

Throughout a vast portion of the North Atlantic Ocean and adjacent Europe, storminess and wind strength appear to have been inversely related to mean global air temperature over most of the past two millennia, with the most frequent and intense events occurring both prior to and following the Medieval Warm Period. The model-based claim that Europe will experience more intense and frequent windstorms if air temperatures continue to rise fails to resonate with reality.

Although some studies suggest there has been a recent increase in storminess across the United Kingdom, others have shown that as Earth has recovered from the global chill of the Little Ice Age, there has been no significant increase in either the frequency or intensity of stormy weather in this area. In fact, most studies suggest just the opposite.

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7.7.1.2.3 Other Regions

Bielec (2001) analyzed thunderstorm data from Cracow, Poland, for the period 1896–1995, finding an average of 25 days of such activity per year, with a non-significant linear-regression-derived increase of 1.6 storm days from the beginning to the end of the record. From 1930 onward, the trend was negative, revealing a similarly derived decrease of 1.1 storm days. In addition, there was a decrease in the annual number of thunderstorms with hail over the entire period and a decrease in the frequency of storms producing precipitation in excess of 20 mm.

Similar findings were reported by the same author two years later (Bielec-Bakowska, 2003) for thunderstorm occurrences at seven Polish synoptic weather stations (Hel, Szczecin, Koszalin, Poznan, Wroclaw, Raciborz, and Krakow) over the period 1885–2000. In this second study the University of Silesia scientist determined "over an annual period of 116 years, no clear trends of changes in the number of days with thunderstorms in Poland were found," noting also "interannual variability of days with thunderstorms in individual seasons did not show any specific trend," except in the winter season, and then only for Szczecin, Krakow, and Koszalin. These findings led her to state "the analysis did not unequivocally confirm the opinion that the number of thunderstorms in the cold part of the year increases," and "a similar phenomenon was observed in the whole of Europe."

With the perspective of anthropogenic climate change, Barring and von Storch (2004) point out, the occurrence of extreme events such as windstorms may "create the perception that ... the storms lately have become more violent, a trend that may continue into the future." Intending to test this inference, and relying on data rather than perception to address the topic, the two researchers analyzed long time series of pressure readings for Lund (since 1780) and Stockholm (since 1823), Sweden, analyzing the annual number of pressure observations below 980 hPa, the annual number of absolute pressure tendencies exceeding 16 hPa/12h, and intra-annual 95th and 99th%iles of the absolute pressure differences between two consecutive observations. They determined the storminess time series they developed "are remarkably stationary in their mean, with little variations on time scales of more than one or two decades." For example, they note "the 1860s–70s was a period when the storminess indices showed general higher values," as was the 1980s–1990s, but subsequently, "the indices have returned to close to their long-term mean."

Barring and von Storch conclude their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." During "the entire historical period," storminess was "remarkably stable, with no systematic change and little transient variability."

Noting "a great amount of evidence for changing storminess over northwestern Europe is based on indirect data and reanalysis data rather than on station wind data," Smits *et al.* (2005) investigated trends in storminess over the Netherlands based on hourly records of 10-m wind speed observations made at 13 meteorological stations across the country with uninterrupted records for the time period 1962–2002. They report "results for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands [of] between 5 and 10% per decade."

Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, to determine historical trends of surges and anomalies. This work revealed no definite trends in weak and moderate positive surges, while strong positive surges clearly became less frequent, even in the face of a gradually rising sea level, "presumably," in the words of Raicich, "as a consequence of a general weakening of the atmospheric activity," also found to have been the case for Brittany (France) by Pirazzoli (2000).

Barredo (2010) examined large historical windstorm event losses in Europe over the period 1970–2008 for 29 European countries. After adjusting the data for "changes in population, wealth, and inflation at the country level and for inter-country price differences using purchasing power parity," the researcher, employed by the Institute for Environment and Sustainability, European Commission-Joint Research Centre in Ispra, Italy, reported "the analyses reveal no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure," adding "increasing disaster losses are overwhelmingly a consequence of changing societal factors."

Additional evidence for the recent century-long decrease in storminess in and around Europe comes from Bijl *et al.* (1999), who analyzed long-term sea-level records from several coastal stations in northwest Europe. They report, "although results show considerable natural variability on relatively short (decadal) time scales," there is "no sign of a significant increase in storminess ... over the complete time period of the data sets." In the southern portion of the North Sea, where natural variability was more moderate, they found a trend, but it was "a tendency towards a weakening of the storm activity over the past 100 years."

Stoffel *et al.* (2005) note debris flows are a type of mass movement that frequently causes major destruction in alpine areas; since 1987, they report, there had been an apparent above-average occurrence of such events in the Valais region of the Swiss Alps, prompting some researchers to suggest the increase was the result of global warming (Rebetez *et al.*, 1997). Stoffel *et al.* used dendrochronological methods to determine whether the recent increase in debris-flow events was indeed unusual, and if so whether it made sense to attribute the increase to CO_2-induced global warming.

In extending the history of debris-flow events (1922–2002) back to the year 1605, they found "phases with accentuated activity and shorter recurrence intervals than today existed in the past, namely after 1827 and until the late nineteenth century." The nineteenth century period of high-frequency debris flow was shown to coincide with a period of higher flood activity in major Swiss rivers, and less frequent debris flow activity after 1922 corresponded with lower flooding frequencies. Debris flows from extremely large mass movement events, similar to what occurred in 1993, were found to have "repeatedly occurred" in the historical past, and to have been of such substantial magnitude that, in the opinion of Stoffel *et al.*, the "importance of the 1993 debris-flow surges has to be thoroughly revised."

Stoffel *et al.*'s work demonstrates the apparent above-average number of debris flow events since 1987 was only that—apparent. They report debris flows occurred "ever more frequently in the nineteenth century than they do today." They conclude, "correlations between global warming and modifications in the number or the size of debris-flow events, as hypothesized by, e.g., Haeberli and Beniston (1998), cannot, so far, be confirmed in the study area."

These findings clearly demonstrate the importance of evaluating the uniqueness of Earth's contemporary climatic state—or the uniqueness of recent trends in various climate-related phenomena—over a much longer timespan than just the past century or, even worse, merely a portion of it. Only when a multicentennial or millennial view of the subject is available can one adequately evaluate the uniqueness of a climate-related phenomenon's recent behavior, let alone link that behavior to late twentieth century or early twenty-first century global warming.

Other studies reveal important conclusions with respect to trends in storminess when examining a timescale much longer than 100 years. Ogrin (2007) presented "an overview of severe storms and a reconstruction of periods with their reiterative occurrence in sub-Mediterranean Slovenia in the warm half of the year during the so-called pre-instrumental period," based on "data gathered in secondary and tertiary historical sources." Speaking of "violent storms" and "the periods in which these phenomena were more frequent and reached, as to the costs of damage caused, the level of natural disasters or even catastrophes," Ogrin reports "the 17th and 18th centuries were undoubtedly such periods, particularly their first halves, when besides storms also some other weather-caused natural disasters occurred quite often, so that the inhabitants, who mainly depended on the self-subsistent agriculture, could not recover for several years after some consecutive severe rigours of the weather." In addition, he reports "the frequency of violent storms in that time was comparable to the incidence towards the end of the 20th century."

Ogrin, who is in the Department of Geography of the University of Ljubljana, writes the late twentieth century increase in violent storms "is supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere." However, he reports "the damage done by severe storms in the past does not differ significantly from the damage in the present." This suggests the weather extremes of today, which he says are "supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere," may in fact be caused by something else, for if they have occurred in the past for a different reason (and they have), they can be occurring today for a different reason too.

Clarke and Rendell (2009) also recognized "an understanding of the patterns of past storminess is particularly important in the context of future anthropogenically driven climate change," especially in light of "predictions of increased storm frequency ... by the end of the current century." They reviewed evidence for storm activity across the North Atlantic region derived from instrumental records and archival evidence of storm impacts, which they then compared to sedimentological and chronological evidences of sand movement and dune building along western European coasts.

The two UK researchers determined "the most notable Aeolian sand drift activity was concentrated in the historic period 0.5–0.1 ka (AD 1500–1900) which spans the Little Ice Age." They state "within this period, low solar activity, during the Maunder (AD 1645–1715) and Dalton (AD 1790–1830) Minima, has been related to changes in Atlantic storm tracks (van der Schrier and Barkmeijer, 2005), anomalously cold winter and summer temperatures in Scandinavia (Bjerknes, 1965), and the repositioning of the polar front and changing sea ice cover (Ogilive and Jonsson, 2001)." In addition, they state "the Holocene record of sand drift in western Europe includes episodes of movement corresponding to periods of Northern Hemisphere cooling (Bond *et al.*, 1997) ... and provides the additional evidence that these periods, like the Little Ice Age, were also stormy," further suggesting any future global warming would more likely result in less, rather than more, storminess in that part of the planet.

Based on optically stimulated luminescence (OSL) dating of the coastal sediment succession, Riemann *et al.* (2011) established "a detailed and reliable chronology" of the Swina barrier at the southern end of the Baltic Sea, two sandy spits or depositional landforms (Wolin and Uznam) that extend outward from the seacoast. This sediment history revealed much about the climate history of the region. Following the Roman Warm Period, which the five researchers say "is known for a moderate and mild climate in Europe" that produced brown foredunes, there was a hiatus between the brown and yellow dunes from 470 AD to 760 AD that "correlates with a cold and stormy period that is known as the Dark Ages Cold Period," which they say "is well known as a cooling event in the climatic records of the North Atlantic (Bond *et al*., 1997; McDermott *et al*., 2001) and in marine sediment cores from Skagerrak (Hass, 1996)," and which also was associated with a phase of increased aeolian activity in northeast England reported by Wilson *et al*. (2001).

Next, as expected, came the Medieval Warm Period. And finally, Riemann *et al*. write, "the cold and stormy Little Ice Age (Hass, 1996) correlates to the formation of the transgressive white dune I in the sediment successions, which were dated to between 1540 and 1660 AD." They note, "the Little Ice Age is documented in North and West Europe in plenty of coastal dunefields, and resulted in sand mobilisation and development of transgressive dunes (e.g., Clemmensen *et al*., 2001a,b, 2009; Wilson *et al*., 2001, 2004; Clarke *et al*., 2002; Ballarini *et al*., 2003; Clemmensen and Murray, 2006; Aagaard *et al*., 2007; Sommerville *et al*., 2007; Clarke and Rendell, 2009)," due to a colder climate and increased storminess related to periodic shifts of the North Atlantic Oscillation (Dawson *et al*., 2002).

Noting "the systematic accretion of foredunes is accompanied by a moderate climate and a progressive plant cover," the German and Polish scientists say foredune instability is "related to aeolian sand mobilisation within phases of a decreased plant cover caused by colder and stormier conditions." These numerous sets of dune-derived data clearly demonstrate that in this particular part of the world warming brings less storminess.

Remarking that "the Mediterranean region is one of the world's most vulnerable areas with respect to global warming," citing Giorgi (2006), Sabatier *et al*. (2012) produced a high-resolution record of paleostorm events along the French Mediterranean coast over the past 7,000 years. According to the nine French scientists, their work "recorded seven periods of increased storm activity at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400, and 400–50 cal yr BP." They associate the latter interval with the Little Ice Age. "In contrast," they state, their results show "the Medieval Climate Anomaly (1150–650 cal yr BP) was characterized by low storm activity." In addition, they note these changes in coastal hydrodynamics were in phase with those observed over the Eastern North Atlantic by Billeaud *et al*. (2009) and Sorrel *et al*. (2009), and the periods of increased storminess they identified seem to correspond to periods of Holocene cooling detected in the North Atlantic by Bond *et al*. (1997, 2001), together with decreases in sea surface temperature reported by Berner *et al*. (2008), who they also say "associated this high frequency variation in sea surface temperature with ^{14}C production rates, implying solar-related changes are an important underlying mechanism for the observed ocean climate variability."

Sabatier *et al*. conclude "whatever the ultimate cause of these millennial-scale Holocene climate variations, the main decreases of sea surface temperature observed in the North Atlantic seem to be an important mechanism to explain high storm activity in the NW Mediterranean area." Their together with those of the others they cite, suggest if Earth's climate continues to warm, for whatever reason, storm activity in the Northwest Mediterranean area will likely significantly subside.

Barring and Fortuniak (2009) point out "extra-tropical cyclone frequency and intensity are currently under intense scrutiny because of the destruction recent windstorms have brought to Europe." They note "several studies using reanalysis data covering the second half of the 20th century suggest increasing storm intensity in the northeastern Atlantic and European sector." They analyzed the "inter-decadal variability in cyclone activity over northwestern Europe back to AD 1780 by combining information from eight storminess indices applied in a Eulerian framework," indices that "use the series of thrice-daily sea level pressure observations at Lund and Stockholm" in Scandinavia.

The two Swedish scientists say their results show former reanalysis studies "cover a time period chiefly coinciding with a marked, but not exceptional in our 225-year perspective, positive variation in the regional cyclone activity that has more recently reversed," noting "because of the inter-decadal variations, a near-centennial time perspective is needed when analyzing variations in extra-tropical cyclone activity and the associated weather conditions over northwestern Europe." By taking this more long-term approach, the two researchers found "there is no significant overall long-term trend common to all indices in cyclone activity in the North Atlantic and European region since the Dalton minimum"; "the marked positive trend beginning around 1960 ended in the mid-1990s and has since then reversed"; and "this positive trend was more an effect of a 20th-century minimum in cyclone activity around 1960, rather than extraordinary high values in [the] 1990s."

Clemmensen *et al*. (2007) examined sedimentological and geomorphological properties of the dune system on the Danish island of Anholt, finding "the last aeolian activity phase on Anholt (AD 1640–1900) is synchronous with the last part of the Little Ice Age." The team of researchers further note "dune stabilization on Anholt seems to a large degree to have been natural, and probably records a decrease in storminess at the end of the 19th century and the beginning of the 20th century," and this timing "is roughly simultaneous with dunefield stabilization on the west coast of Jutland and on Skagen Odde," citing the work of Clemmensen and Murray (2006).

Bjorck and Clemmensen (2004) extracted cores of peat from two raised bogs in the near-coastal part of southwest Sweden, from which they derived histories of wind-transported clastic material via systematic counts of quartz grains of various size classes that enabled them to calculate temporal variations in Aeolian Sand Influx (ASI), which has been shown to be correlated with winter wind climate in that part of the world. They found "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," and "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

The two researchers also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they state an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)." They also find high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting this period coincides with the Sporer Minimum of AD 1420–1530. In addition, they note the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

The two researchers also report degree of humification (DOH) intervals "correlate well with the classic late-Holocene climatic intervals," which they specifically state to include the Modern Climate Optimum (100–0 cal. yr BP), the Little Ice Age (600–100 cal. yr BP), the Medieval Warm Period (1250–600 cal. yr BP), the Dark Ages Cold Period (1550–1250 cal. yr BP), and the Roman Climate Optimum (2250–1550 cal. yr BP). There would thus appear to be little doubt that winter storms throughout southern Scandinavia were more frequent and intense during the multicentury Dark Ages Cold Period and Little Ice Age than during the Roman Warm Period, Medieval Warm Period, and Current Warm Period, providing strong evidence to refute the contention that storminess tends to increase during periods of greater warmth.

As Earth has recovered from the global chill of the Little Ice Age, there appears to have been no significant increase in either the frequency or intensity of stormy weather in many regions across Europe. Most studies suggest just the opposite. There is no real-world or data-driven reason to believe storms would necessarily get any worse or become more frequent if Earth were to warm somewhat more in the future.

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7.7.1.3 North America

7.7.1.3.1 Canada

Recognizing "media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe weather events," Hage (2003) set out to test this hypothesis in the prairie provinces of Alberta and Saskatchewan in western Canada. The author utilized "previously unexploited written resources such as daily and weekly newspapers and community histories" to establish a database adequate for determining long-term trends of all destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) for the region over the period 1882–2001. Hage notes because "sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns, … extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors." Hage found "all intense storms showed no discernible changes in frequency after 1940."

Lawson (2003) examined the occurrence of blizzards at a number of locations within the Prairie Ecozone of western Canada, analyzing trends in occurrence and severity over the period 1953–1997. No significant trends were found in central and eastern locations. In the western prairie locations, the author found a significant downward trend in blizzard frequency, noting "this trend is consistent with results found by others that indicate a decrease in cyclone frequency over western Canada." He also notes the blizzards that do occur "exhibit no trend in the severity of their individual weather elements." These observed trends "serve to illustrate that the changes in extreme weather events anticipated under Climate Change may not always be for the worse."

Gascon *et al.* (2010) conducted a study they describe as "the first to document the climatology of major cold-season precipitation events that affect southern Baffin Island." They examined the characteristics and climatology of the 1955–2006 major cold-season precipitation events at Iqaluit, the capital of Nunavut, located on the southeastern part of Baffin Island in the northwestern end of Frobisher Bay, basing their work on analyses of hourly surface meteorological data obtained from the public archives of Environment Canada. The precipitation data were corrected to account for gauge catchment errors due to wind effects, snow-water equivalence variations, and human error in the manually retrieved precipitation data for the period 1955–1996; the remaining data were used in their uncorrected state.

The three researchers detected a non-significant decrease in autumn and winter storm activity over the period of their study, which they say comports with the results of Curtis *et al.* (1998), who observed a concomitant decrease in annual precipitation in the western Arctic. This was true in spite of the findings of Zhang *et al*. (2004), who Curtis *et al.* say "reported an increase in cyclonic activity over the past fifty years, as well as McCabe *et al*. (2001), Wang *et al.* (2004) and Yin (2005)," who reported a northward shift in such activity. That shift apparently was not great enough to "translate into major precipitation events, or at least not in Iqaluit," as revealed by the authors' results depicted in Figure 7.7.1.3.1.1.

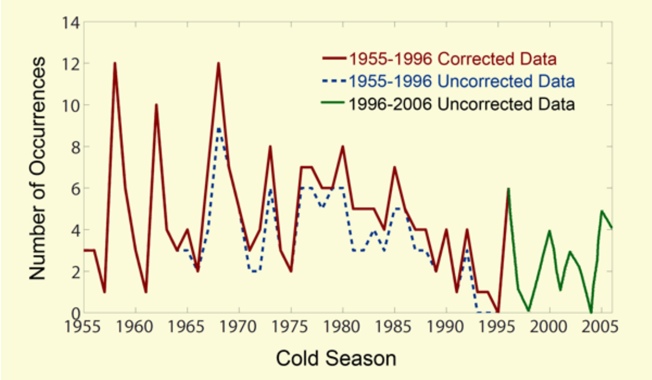

Figure 7.7.1.3.1.1. Cold-season occurrences of major precipitation events at Iqaluit, Nunavut, Canada. Adapted from Gascon, G., Stewart, R.E., and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327–337.

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7.7.1.3.2 Alaska

Hudak and Young (2002) examined the number of fall (June–November) storms in the southern Beaufort Sea region based on criteria of surface wind speed for the relatively short period of 1970–1995. Although there was considerable year-to-year variability in the number of storms, there was no discernible trend over the 26-year period in this region of the globe, where climate models predict the effects of CO_2-induced global warming to be most evident.

Mason and Jordan (2002) studied numerous depositional environments along the tectonically stable, unglaciated eastern Chuckchi Sea coast that stretches across northwest Alaska, deriving a 6,000-year record of sea-level change. They learned "in the Chukchi Sea, storm frequency is correlated with colder rather than warmer climatic conditions." Consequently, they say their data "do not therefore support predictions of more frequent or intense coastal storms associated with atmospheric warming for this region."

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7.7.1.3.3 Eastern USA

Zhang *et al*. (2000) used ten long-term records of storm surges derived from hourly tide gauge measurements to calculate annual values of the number, duration, and integrated intensity of storms in this region. Their analysis did not reveal any trends in storm activity during the twentieth century, which they say is suggestive of "a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr."

Similar results were reported by Boose *et al*. (2001), who examined historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They discerned "no clear century-scale trend in the number of major hurricanes." For the most recent and reliable 200-year portion of the record, however, the cooler nineteenth century had five of the highest-damage F3 category storms, whereas the warmer twentieth century had only one such storm.

Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York between 1851 and 2005 to assess the degree of likelihood that twentieth century global warming might be influencing these storms. According to the author, "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and of these storms, "14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms." For Long Island in particular, he further reports "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." He found storm activity was greatest in the late nineteenth century and late twentieth century, and "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century." Vermette thus concludes, "rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century."

Noren *et al*. (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km^2 region of Vermont and eastern New York. They found "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." The most recent upswing in storminess did not begin with what the IPCC calls the unprecedented warming of the twentieth century, but "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." The authors conclude the increase in storminess was likely a product of natural changes in the Arctic Oscillation.

Mallinson *et al*. (2011) employed optically stimulated luminescence (OSL) dating of inlet-fill and flood tide delta deposits from locations in the Outer Banks barrier islands of North Carolina to provide a "basis for understanding the chronology of storm impacts and comparison to other paleoclimate proxy data" in the region over the past 2,200 years. Analyses of the cores revealed "the Medieval Warm Period (MWP) and Little Ice Age (LIA) were both characterized by elevated storm conditions as indicated by much greater inlet activity relative to today." They write, "given present understanding of atmospheric circulation patterns and sea-surface temperatures during the MWP and LIA, we suggest that increased inlet activity during the MWP responded to intensified hurricane impacts, while elevated inlet activity during the LIA was in response to increased nor'easter activity." The group of five researchers state their data indicate, relative to climatic conditions of the Medieval Warm Period and Little Ice Age, there has more recently been "a general decrease in storminess at mid-latitudes in the North Atlantic," reflecting "more stable climate conditions, fewer storm impacts (both hurricane and nor'easter), and a decrease in the average wind intensity and wave energy field in the mid-latitudes of the North Atlantic."

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7.7.1.3.4 Central and Southern USA

Bove *et al*. (1998) studied land-falling hurricanes whose eyes crossed the coast between Cape Sable, Florida and Brownsville, Texas between 1896 and 1995, finding the first half of the twentieth century had more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. The same is true for intense hurricanes of category 3 on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes have been trending downward since 1966, with the decade starting in 1986 exhibiting the fewest intense hurricanes of the century.

Liu and Fearn (1993) studied major storms along the U.S. Gulf Coast over the past 3,500 years. Using sediment cores taken from the center of Lake Shelby in Alabama, they determined "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years," with the last of these superstorms occurring around 700 years ago. They further note "climate modeling results based on scenarios of greenhouse warming predict a 40%–50% increase in hurricane intensities in response to warmer tropical oceans." If one of these severe storms (about a century overdue) were to hit the Alabama coast, it would be nothing more than an illustration of the age-old adage that history repeats itself.

Muller and Stone (2001) examined historical data relating to tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island, Texas to Cape Hatteras, North Carolina for the 100-year period 1901–2000. Their analysis revealed the temporal variability of tropical storm and hurricane strikes was "great and significant," with most coastal sites experiencing "pronounced clusters of strikes separated by tens of years with very few strikes." The data did not support the claim of a tendency for increased storminess during warmer El Niño years; for tropical storms and hurricanes together, the authors found an average of 1.7 storms per El Niño season, 2.6 per neutral season, and 3.3 per La Niña season. For hurricanes only, the average rate of occurrence ranged from 0.5 per El Niño season to 1.7 per La Niña season.

Daoust (2003) suggested using tornado days instead of tornado frequencies "provides a more stable data set which should allow a more accurate analysis of the phenomenon." Daoust catalogued daily tornado frequencies for each county of Missouri, USA, for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state's 115 counties, its six climatic divisions, and the entire state. Results indicated the presence of positive trends in the tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant, but negative. At the state level, Daoust reports "for the last 53 years, no long-term trend in tornado days can be found."

Changnon (2001) compared thunderstorm activity at both an urban and rural location in Chicago to determine whether there might be an urban influence on thunderstorm activity. Over the 40-year period investigated (1959–1998), he found the urban station experienced an average of 4.5 (12%) more thunderstorm days per year than the more rural station, and statistical tests revealed this difference to be significant at the 99% level in all four seasons of the year. This finding should elicit further caution in interpreting storm trend studies, many of which are based on data obtained from urban locations, which in the case of thunderstorms in Chicago, skewed the observational data upwards.

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7.7.1.3.5 Conterminous USA

Hayden (1999) investigated storm frequencies between 25° and 55°N latitude and 60° and 125°W longitude from 1885 to 1996. Over this 112-year period, he reports, large regional changes in storm occurrences were observed, but when integrated over the entire geographic area, no net change in storminess was evident.

Similar results were noted by Changnon and Changnon (2000), who examined hail-day and thunder-day occurrences over the 100-year period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the country. They found the frequency of thunder-days peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Thereafter, both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence decreased to only 65% of what it was at mid-century, accompanied by a drop in national hail insurance losses over the same period.

Several years later, the authors conducted an analysis of snowstorms. Changnon and Changnon (2006) point out "global climate models predict that more weather extremes will be a part of a changed climate due to greenhouse gases," and such a climate change "is anticipated to result in alterations of cyclone activity over the Northern Hemisphere (Lawson, 2003)." They also note "a change in the frequency, locations, and/or intensity of extratropical cyclones in the mid-latitudes would alter the incidence of snowstorms," citing the work of Trenberth and Owen (1999).

The authors conducted "a climatological analysis of the spatial and temporal distributions of ... damaging snowstorms and their economic losses … using property-casualty insurance data that consist of highly damaging storm events, classed as catastrophes by the insurance industry, during the 1949–2000 period." In support of this approach to the subject, they report the National Academy of Sciences has identified insurance catastrophe data as "the nation's best available loss data (National Research Council, 1999)."

The father-and-son research team reports "the incidence of storms peaked in the 1976–1985 period," but snowstorm incidence "exhibited no up or down trend during 1949–2000," although national monetary losses did have a significant upward time trend indicative of "a growing societal vulnerability to snowstorms." The two researchers conclude, "the temporal frequency of damaging snowstorms during 1949–2000 in the United States does not display any increase over time, indicating that either no climate change effect on cyclonic activity has begun, or if it has begun, altered conditions have not influenced the incidence of snowstorms."

Schwartz and Schmidlin (2002) compiled a database of blizzards for the years 1959–2000 for the conterminous United States. A total of 438 blizzards were identified in the 41-year record, yielding an average of 10.7 blizzards per year. Year-to-year variability was significant, with the number of annual blizzards ranging from a low of 1 in the winter of 1980–1981 to a high of 27 during the winter of 1996–1997. Linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period; the total area affected by blizzards each winter remained relatively constant and showed no trend. If these observations are both correct, then average blizzard size is much smaller now than it was four decades ago. As the authors note, however, "it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

The work of Schwartz and Schmidlin suggests the frequency of U.S. blizzards may have increased, but intensity likely decreased. Alternatively, the authors suggest the reported increase in blizzard frequency may be due to an observational bias that developed over the years, for which there is a known analogue in the historical observation of tornadoes. That this possibility is likely a probability is suggested by the study of Gulev *et al.* (2001), who analyzed trends in Northern Hemispheric winter cyclones over essentially the same time period (1958–1999) and found a statistically significant decline of 1.2 cyclones per year using NCEP/NCAR reanalysis pressure data.

Balling and Cerveny (2003) reviewed the scientific literature to determine what has been learned from United States weather records about severe storms during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense precipitation, tornadoes, hurricanes, and winter storm activity. They report several scientists have identified an increase in heavy precipitation, but "in other severe storm categories, the trends are downward."

Kunkel (2003) reports a sizable increase in the frequency of extreme precipitation events in the United States since the 1920s and 1930s, but notes the frequencies of the late 1800s and early 1900s were about as high as those of the 1980s and 1990s, which suggests there may have been no century-long increase in this type of extreme weather.

Changnon (2003a) utilized a newly available extensive dataset on thunderstorm days covering the period 1896–1995 to assess long-term temporal variations in thunderstorm activity at 110 first-order weather reporting stations across the United States. By dividing the data into five 20-year segments, Changnon found "the 1936–1955 period was the nation's peak of storm activity during the 100-year period ending in 1995." During this central 20-year period, 40% of the 110 first-order weather stations experienced their greatest level of storm activity, whereas during the final 20-year period from 1976–1995, only 15% of the stations experienced their greatest level of storm activity.

In a separate paper, Changnon (2003b) investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States, finding mixed results. For example, he reports "one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms)." As mentioned earlier, however, had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon likely would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

Insurance losses, by contrast, rose rapidly over the past several decades, Changnon found, the primary reason being "a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society's vulnerability." When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events "do not exhibit an upward trend." Thus, as Changnon emphasizes, "the adjusted loss values for these extremes [do] not indicate a shift due to global warming." He reiterates these real-world observations "do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO_2 levels, that call for weather extremes and storms to increase in frequency and intensity."

Similar findings with respect to monetary loss trends due to extreme storm events were reported again by Changnon three years later in two separate papers.

In the first of these papers, working with data from the insurance industry, the researcher from the Illinois State Water Survey analyzed "catastrophes caused solely by high winds" that had had their losses adjusted so as to make them "comparable to current year [2006] values" (Changnon, 2009a). Although the average monetary loss of each year's catastrophes "had an upward linear trend over time, statistically significant at the 2% level," when the number of each year's catastrophes was considered, "low values occurred in the early years (1952–1966) and in later years (1977–2006)," and "the peak of incidences came during 1977–1991." Thus it was not surprising, as Changnon describes it, that "the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend."

In his second paper from 2009, Changnon (2009b) utilized "records of extremely damaging storms in the United States during the years 1949–2006 … to define their temporal distribution," where such storms were defined as those producing losses greater than $100 million, with a special subset defined as those producing losses greater than $1 billion. At this extreme level of classification it was clearly evident "the number of storms at both loss levels has increased dramatically since 1990." The author presents four possible explanations for his findings. First, he notes "storm measurement and data collection have improved over time." Second and third, he says "the increases may also reflect natural variations in climate or a shift in climate due to global warming." He then states "a fourth reason is that society has become more vulnerable to storm damages."

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7.7.1.4 Other Regions

Sorrel *et al.* (2012) note the southern coast of the English Channel in northwestern France is "well suited to investigate long-term storminess variability because it is exposed to the rapidly changing North Atlantic climate system, which has a substantial influence on the Northern Hemisphere in general." They present "a reappraisal of high-energy estuarine and coastal sedimentary records," finding "evidence for five distinct periods during the Holocene when storminess was enhanced during the past 6,500 years."

The six scientists say "high storm activity occurred periodically with a frequency of about 1,500 years, closely related to cold and windy periods diagnosed earlier (Bond *et al.*, 2001; Wanner *et al.*, 2008; Wanner *et al.*, 2011)." They show "millennial-scale storm extremes in northern Europe are phase-locked with the period of internal ocean variability in the North Atlantic of about 1,500 years (Debret *et al.*, 2009)," with the last extreme stormy period "coinciding with the early to mid-Little Ice Age." They note "in contrast, the warm Medieval Climate Optimum was characterized by low storm activity (Sorrel *et al.*, 2009; Sabatier *et al.*, 2012)." Sorrel *et al.* conclude, "in light of concerns about the impact of anthropogenic greenhouse gases on extreme storm events in the coming years/decades, our results indicate that modern coupled ocean-atmosphere dynamics at North Atlantic mid-latitudes should tend towards the low phase of the 1,500-year internal oceanic cycle, in contrast to Little Ice Age climate conditions," which suggests warming should lead to relatively less storminess, contrary to what the models project.

Gulev *et al.* (2001) utilized sea-level pressure from NCEP/NCAR reanalysis data for the period 1958–1999 to develop a winter (January–March) climatology of cyclones (storms) for the Northern Hemisphere, from which they statistically analyzed only those cyclones that reached a sea-level pressure of 1000 mb or lower. They found the yearly mean number of winter cyclones for the period was 234, although there was pronounced interannual and spatial variability in the record. Linear trend estimates indicated a statistically significant (95% level) annual decline of 1.2 cyclones per year, suggesting there were 50 fewer cyclones in the Northern Hemisphere winter at the end of the record than there were 42 years prior (Figure 7.7.1.4.1). Additional data analyses suggest Northern Hemisphere winter cyclones are intensifying at quicker rates and are reaching greater maximum depths (lower sea-level pressure) at the end of the record than they were at the beginning of the record. However, the wintertime cyclones are also experiencing shorter life cycles, dissipating more quickly at the end of the record than at the beginning.

Winter storms in North America at the end of the

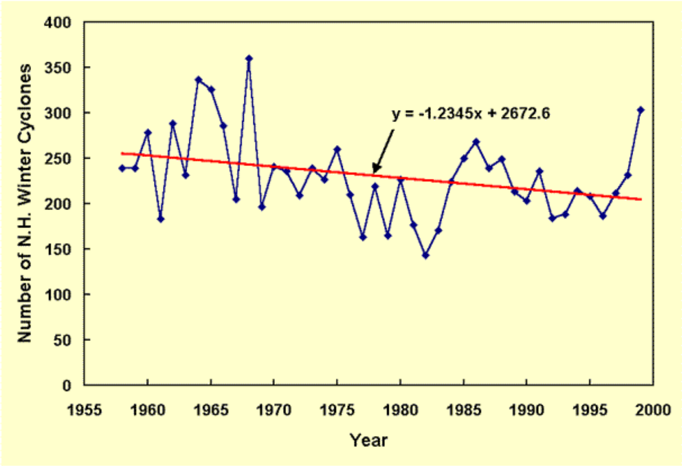

Figure 7.7.1.4.1. Yearly number of Northern Hemisphere cyclones over the period 1958-1999. Adapted from Gulev, S.K., Zolina, O., and Grigoriev, S. 2001. Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics* **17**: 795–809.

twentieth century thus appear to have been maturing faster but dissipating more quickly than they were four decades earlier. Could this change be the result of global warming? The authors say the phenomenon is probably connected to large-scale features of atmospheric variability, such as the North Atlantic Oscillation and the North Pacific Oscillation. As for the large decrease reported in the annual number of Northern Hemisphere cyclones over the 42-year period, this observation is in direct opposition to model-based extreme weather predictions, which suggest the frequency of such events will increase as a result of global warming.

Simmonds and Keay (2000) employed a new cyclone finding and tracking scheme to conduct what they say "is arguably the most reliable analysis of Southern Hemisphere cyclone variability undertaken to date." They found the annual average number of cyclones in the Southern Hemisphere steadily increased from the start of the assessment period. After peaking in 1972, however, there was an overall decline, and the authors state "the counts in the 1990s have been particularly low." They detected a small increase in mean cyclone radius, but they note this effect has only "served to partially offset the effect of the remarkable decrease in cyclone numbers." They also note the time series of Southern Hemisphere cyclone numbers shows an out-of-phase relationship with the Southern Hemisphere mean annual temperature record, which suggests, in their words, "that the downward trends in cyclone numbers are associated with a warming Southern Hemisphere."

Yu *et al*. (2004) point out, "according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones." Because "understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events," they devised a way to decipher the history of severe storms in the region of the southern South China Sea. At Youngshu Reef (9°32'–9°42'N, 112°52–113°04'E), they used standard radiocarbon dating and TIMS U-series dating to determine the times of occurrence of storms strong enough to "relocate" large *Porites* coral blocks widespread on the reef flats there. Yu *et al*. determined "during the past 1000 years, at least six exceptionally strong storms occurred," which they dated to approximately 1064 ± 30, 1218 ± 5, 1336 ± 9, 1443 ± 9, 1682 ± 7, and 1872 ± 15 AD, yielding an average recurrence frequency of 160 years. Although models typically suggest that storms will become more frequent and severe in response to global warming and the warming of the twentieth century was the most significant of the past millennium, none of the six severe storms identified by Yu *et al*. occurred during the past millennium's last century.

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7.7.1.5 Global

Although most studies focus on storms trends for a given location or region, some researchers have attempted to examine the trends for the globe as a whole. This section reviews that research.

Huntington (2006) states there is "a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al*., 1991; Loaciga *et al*., 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al*., 2001)." He reiterates the long-held climate-model-derived notion that "an intensification of the water cycle may lead to changes in water-resource availability," meaning "floods and droughts," as well as "an increase in the frequency and intensity of tropical storms." He proceeds to explore these theoretical expectations via a review of the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and other parameters.

"On a globally averaged basis," according to Huntington, "precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al*., 1997; Hulme *et al*., 1998)." He also notes "an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987)," and a recent reanalysis of these trends for the period 1920–1995 "confirmed an increase in world continental runoff during the 20th century (Labat *et al*., 2004)."

These findings suggest global warming may indeed have intensified the global hydrologic cycle over the twentieth century. However, Huntington also reports "the empirical evidence to date does not consistently support an increase in the frequency or intensity of tropical storms and floods." As for droughts, he says the "evidence indicates that summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al*., 2000)."

Thus there appears to have been a slight intensification of the hydrologic cycle throughout the twentieth century over Earth's land area, which may or may not have been caused by the concomitant warming of the globe, but it also appears there was no intensification of deleterious weather phenomena such as tropical storms, floods, and droughts. In addition, Smith *et al*. (2006) demonstrate over the period 1979–2004, when the IPCC claims the planet experienced a warming unprecedented over the past one to two millennia, there was no net change in global precipitation (over both land and water).

Gulev and Grigorieva (2004) analyzed ocean wave heights (a proxy for storms) using the Voluntary Observing Ship wave data of Worley *et al*. (2005) to characterize significant wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists report "the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950," which would seem to vindicate model projections of increasing storms. "However," they continue, "for the period 1885–2002 there is no secular trend in HS in the Atlantic" and "the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002."

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century "is comparable with that for recent decades," and "in the Atlantic it is even higher than during the last 5 decades.” In the Atlantic the mean HS of the decade of the 1920s is higher than that of any recent decade, and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific it also appears the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes a definitive answer on this point. Nevertheless, it is clear that annual mean wave height (a proxy for storminess) over the last decade of the twentieth century was not higher than annual wave height values earlier in the century.

Key and Chan (1999) analyzed trends in seasonal and annual frequencies of low-pressure centers (cyclones) at 1000-mb (near-surface) and 500-mb heights for six latitude regions (0–30°N, 0–30°S, 30–60°N, 30–60°S, 60–90°N and 60–90°S) over the four-decade period 1958–1997, while also determining trends in cyclone frequencies for El Niño vs. La Niña years. They found both positive and negative trends (some significant and some not) in cyclone frequency at both atmospheric levels over the 40-year period. Cyclone frequencies at both atmospheric levels were also found to be lower at all latitude regions except two (30–60°S and 60–90°S) during El Niño years, as opposed to La Niña years. Although Key and Chan found some regional differences in cyclone frequencies, there was no indication of any global trend, positive or negative. They also found fewer cyclones occur during warmer El Niño years than during cooler La Niña years, appearing to further invalidate model-based claims that global warming will result in more storms globally..

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7.7.2 Dust Storms

Will dust storms increase in response to CO_2-induced global warming? That question requires an answer given model-based projections that both the frequency and intensity of extreme weather events will increase in the future.

According to Griffin *et al.* (2002), "as much as two billion metric tons of dust are lifted into the Earth's atmosphere every year," and soil particulates from Africa and Asia cross both the Atlantic and Pacific Oceans. As a result of the trans-Pacific transport, Wilkening *et al.* (2000) state "the once-pristine air above the North Pacific Ocean is polluted," and they go on to list several implications for a number of terrestrial and oceanic ecosystems. They also note we can expect these impacts to increase with economic expansion around the world, and by analogy we can infer such impacts have likely grown in tandem with population and industrialization over the past century or so. Griffin *et al.* remark dust storms originating in North Africa "routinely affect the air quality in Europe and the Middle East," and millions of tons of African sediment "fall on the North Amazon Basin of South America every year."

Prospero (2001) suggests nearly everyone in the United States living east of the Mississippi River is affected by dust of African origin. Likewise, Prospero and Lamb (2003) report measurements made from 1965 to 1998 in the Barbados trade winds show large interannual changes in the concentration of dust of African origin that are highly anticorrelated with the prior year's rainfall in the Soudano-Sahel, and they note the IPCC report of Houghton *et al.* (2001) "assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts." They say "there is little firm evidence to support either of these assumptions."

Griffin *et al.* report in April 2001 a large dust cloud originating over the Gobi Desert of China "moved eastward across the globe, crossing Korea, Japan, the Pacific (in five days), North America (causing sporadic reports of poor air quality in the United States), the Atlantic Ocean and then Europe."

Grousset *et al.* (2003) studied dust samples collected in the French Alps, analyzing their mineralogical and geochemical composition, including the isotopic composition of the neodymium contained in the minerals. They then reconstructed airmass backward trajectories from archived meteorological data, including corroboration by satellite imagery, and used a global transport model driven by assimilated meteorology to simulate dust deflation and long-range transport. Their work revealed one of the sets of dust samples came from North Africa, and the second set originated in the Takla-Makan desert of China. Their work additionally suggested the latter set of dust particles had traveled "more than 20,000 km in about two weeks, and along their journey, crossed China, the North Pacific, North America and then the North Atlantic Ocean." That knowledge, they write, "is important from the viewpoint of understanding the dust itself" as well as "the heavy metal, fungal, bacterial and viral pollution that may be associated with it."

Liu *et al.* (2004) analyzed trends in spring dust storm frequency for western and southwestern China-Mongolia for the period 1952–2003, finding both interannual and interdecadal trends throughout the 52-year period. By decade, the number of spring dust storms varied from 21 in the 1950s, to 44 in the 1960s, to a high of 60 in the 1970s, then back down to 35 in the 1980s, and a low of 25 in the 1990s. In addition, they determined strong and cold Siberian air masses enhance dust storm numbers, whereas weaker and warmer Siberian air masses lower them. Thus, if warming of the globe increases temperatures in the northern part of China and Mongolia, Liu *et al.* say "the China-Mongolia ridge will continue to rise and suppress Mongolian cyclones and dust storm activities in Western China-Mongolia."

Zhu *et al.* (2008) note "changes in occurrences of natural disasters, which are possibly associated with global warming, have been receiving ever-increasing attention world wide," and the "dust storm is one of the severe disastrous weather [phenomena] in China." In this regard, however, and in contrast to the general tenor of most model-based discussions of global warming and extreme weather, they write, "a number of studies have shown that the spring dust storm frequency (DSF) bears a negative correlation with the local surface air temperature, and exhibits a downward trend over the past 50 years," citing the studies of Qian *et al.* (2002), Zhou and Zhang (2003), Zhai and Li (2003), Zhao *et al.* (2004), Fan *et al.* (2006), and Gong *et al.* (2006, 2007).

Zhu *et al.* explored "the long-term variation of Chinese DSF in spring (March to May), and its possible linkage with the global warming and its related circulation changes in the Northern Hemisphere," using data from 258 stations within the region surrounding Lake Baikal (70–130°E, 45–65°N) over the period 1954 to 2007. The authors found a "prominent warming" in recent decades, as well as "an anomalous dipole circulation pattern" in the troposphere that "consists of a warm anti-cyclone centered at 55°N and a cold cyclone centered around

30°N," leading to "a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian regions, which suppress the frequency of occurrence and the intensity of the Mongolian cyclones and result in the decreasing DSF in North China." Rising temperatures, therefore, served as the trigger mechanisms in trends in DSF, but not in the general manner projected by the IPCC: Rising temperatures reduced DSF instead of increasing it.

Lim *et al*. (2005) examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, from which they produced a proxy record of major Asian dust events that reached the region over the past 6,500 years. This analysis indicated the EQC was relatively low 6,500–4,000 years BP, high 4,000–2,000 years BP, and low again from 2,000 years BP to the present, with the most recent 1,500 years BP being lower in EQC than any previous time in the record. The Asian dust time series also was found to contain significant millennial- and centennial-scale periodicities. Cross-spectral analysis between the EQC and proxy solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the three researchers to conclude the centennial-scale periodicities in the EQC can be ascribed primarily to short-term fluctuations in solar activity.

Engelstaedter *et al*. (2003) used dust storm frequency (DSF) data from 2,405 stations represented in the International Station Meteorological Climate Summary as a surrogate measure of dust emissions to test the assumption that vegetation is an important control of dust emission at the global scale. To represent vegetation cover, they used two independent datasets: a satellite-derived distribution of actual vegetation types, and a model-derived distribution of potential natural vegetation. Employing these tools, they learned "the highest DSFs are found in areas mapped by DeFries and Townshend (1994) as bare ground," and "moderate DSFs occur in regions with more vegetation, i.e., shrubs & bare ground, and lowest DSFs occur in grasslands, forests, and tundra," where ground cover is highest. Thus they conclude "average DSF is inversely correlated with leaf area index (an index of vegetation density) and net primary productivity," suggesting whatever increases vegetative cover should reduce the severity of dust emissions from the soil beneath as well as the dust's subsequent transport to various parts of the world.

Evan *et al*. (2006) reached a similar conclusion, applying a new daytime over-water dust detection algorithm for the Advanced Very High Resolution Radiometer (AVHRR) to 24 years (1982–2005) of wintertime satellite imagery over West Africa and the surrounding Atlantic Ocean and comparing it with a similarly derived Normalized Difference Vegetation Index (NDVI) shown to be responsive to vegetation variability in the Sahel. A strong relationship was found to exist between tropical North Atlantic dustiness and the vegetation index, "suggesting the possibility that vegetation changes in the Sahel play an important role in variability of downwind dustiness." Evan *et al*. conclude "dust mobilization may be mediated by vegetation through increases in soil stability and reductions of wind stress on the surface, when more vegetation is present," which "would be consistent with the modeling studies of Gillette (1999) and Engelstaedter *et al*. (2003)."

Rising atmospheric CO_2 might play a valuable role in this regard. The well-documented increase in plant water use efficiency that results from increases in the air's CO_2 content should allow more plants to grow in the arid source regions of Earth's dust clouds, helping stabilize and shield the soil, decreasing its susceptibility to wind erosion and reducing the amounts of dust made airborne and transported by globe-girdling winds. Moreover, the propensity for elevated CO_2 concentrations to increase soil moisture content as a consequence of CO_2-induced reductions in plant transpiration should also encourage plant growth. And the ability of extra atmospheric CO_2 to enhance the growth of cryptobiotic soil crusts should directly stabilize the surface of the soil, even in the absence of higher plants. Direct support for the role of elevated CO_2 in increasing desert biomass is provided by the recent work of Donohue *et al*. (2013), who found foliage has increased over warm, dry regions by 5 to 10% from 1982 to 2010.

We conclude with a review of the findings of Piao *et al*. (2005), who used a "time series data set of Normalized Difference Vegetation Index (NDVI) obtained from the Advanced Very High Resolution Radiometer available from 1982 to 1999 (Tucker *et al*., 2001; Zhou *et al*., 2001), and precipitation and temperature data sets, to investigate variations of desert area in China by identifying the climatic boundaries of arid area and semiarid area, and changes in NDVI in these areas." They found "average rainy season NDVI in arid and semiarid regions both increased significantly during the period 1982-1999." The NDVI increased for 72.3% of total arid regions and for 88.2% of total semiarid regions, such that the area of arid regions decreased by 6.9% and the area of semiarid regions decreased by 7.9%. They also report that by analyzing Thematic Mapper satellite images, "Zhang *et al*. (2003) documented that the process of desertification in the Yulin area, Shannxi Province showed a decreased trend between 1987 and 1999," and "according to the national monitoring data on desertification in western China (Shi, 2003), the annual desertification rate decreased from 1.2% in the 1950s to -0.2% at present."

Noting "variations in the vegetation coverage of these regions partly affect the frequency of sand-dust storm occurrence (Zou and Zhai, 2004)," Piao *et al*. conclude "increased vegetation coverage in these areas will likely fix soil, enhance its anti-wind-erosion ability, reduce the possibility of released dust, and consequently cause a mitigation of sand-dust storms." And, as pointed out in previous studies, they report "recent studies have suggested that the frequencies of strong and extremely strong sand-dust storms in northern China have significantly declined from the early 1980s to the end of the 1990s (Qian *et al*., 2002; Zhao *et al*., 2004)."

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7.7.3 Hail

Insurance costs related to life and property damage caused by extreme weather events have been steadily rising in the United States and elsewhere, and it is not uncommon for many in the insurance industry and government to place the blame for this development on what they claim are significant increases in the frequencies and intensities of severe weather events, since climate models suggest these phenomena should be increasing as a consequence of CO_2-induced global warming. But is this explanation correct?

According to the latest IPCC report, there is "insufficient evidence" to determine whether such small-scale severe weather events as hail are changing in response to what they perceive to be the unprecedented modern rise in both atmospheric CO_2 and temperature (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The following research, however, strongly suggests changes in atmospheric CO_2 and temperature have exerted no measurable influence on hail trends, when hail data are properly analyzed.

After describing and analyzing property losses caused by a series of Midwestern U.S. hailstorms that occurred on 13–14 April 2006, totaling $1.822 billion, "an amount considerably more than the previous record high of $1.5 billion set by an April 2001 hail event," Changnon (2009) described and analyzed the "top ten" hail-loss events that occurred in the United States over the period 1950–2006, finding "an increase over time in [hail event] frequency and losses with most major events occurring since 1990."

These findings would appear to support the contention that global warming is causing more hail events. However, the Illinois State Water Survey researcher opines only "two factors could have affected this increase." One of them, in his words, could have been "more frequent occurrences of major cases of strong atmospheric instability, leading to the development of supercell thunderstorms capable of persisting for many hours, covering large areas, and producing large hailstones." He says this scenario "has not been measured and cannot be verified." The second factor, as he describes it, "is the expansion of the nation's metropolitan areas, enhancing the target for hail damages to property," in support of which he notes "urban population in the U.S. since 1960 increased by 56% and urban areas grew by 154%," according to the World Almanac (2008), making a good case for the second of the two factors Changnon suggests.

This latter explanation also was favored by Changnon in an earlier study (Changnon, 2003) in which he investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century. He found trends in various weather extremes over this period were mixed, noting, "one trend is upwards (heavy rains-floods), others are downward [including "hail, hurricanes, tornadoes, and severe thunderstorms"], and others are unchanging flat trends (winter storms and wind storms)." As for why U.S. insurance losses due to most extreme weather events rose so rapidly throughout the past several decades, Changnon reports “the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society’s vulnerability.”

Further support for this thesis comes from the even earlier work of Kunkel *et al.* (1999), who analyzed historical trends in several different types of extreme weather events, together with their societal impacts, near the close of the last century. They found most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses. However, they found “trends in most related weather and climate extremes do not show comparable increases with time.” These observations led them to conclude the increasing economic losses “are primarily due to increasing vulnerability arising from a variety of societal changes,” and in this regard they found “increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors.”

When the temporal span of analysis is expanded even further, the claim that global warming is increasing hail events is completely debunked. Changnon and Changnon (2000), for example, analyzed hail-day and thunder-day occurrences over the century-long period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the United States. This effort revealed thunder-day frequency peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence fell to only 65% of what it had been at mid-century, dropping so low there was a decline in national hail insurance losses over the final two decades of the study.

Locations beyond the United States yield similar results. Bielec (2001) analyzed thunderstorm data obtained at Cracow, Poland, described as possessing “one of the few continuous records in Europe with an intact single place of observation and duration of over 100 years.” Over the length of this record, there were 2,470 days with thunderstorms, an average of about 25 days per year. The highest annual number of thunderstorm days was 37, recorded in 1968 and again in 1975, and the lowest annual number was 9, in 1904. Close analysis of the data revealed a slight but non-significant linear increase of 1.6 storms per year from the beginning to the end of the record. From 1930 onward, however, the trend is negative, revealing a linear decrease of 1.1 storms per year. With respect to the annual number of thunderstorms with hail, Bielec reports there was a decrease over the hundred-year period.

From a historical hail dataset of 753 stations compiled by the National Meteorological Information Center of China, which “includes hail data for all weather stations in the surface meteorological observational network over the whole of China from 1951 to 2005,” Xie *et al.* (2008) “chose 523 stations with complete observations from 1960 to 2005” to study “annual variations and trend[s] of hail frequency across mainland China during 1960–2005.”

As is evident in Figure 7.7.3.1, Xie *et al.* found “no trend in the mean Annual Hail Days (AHD) from 1960 to [the] early 1980s but a significant decreasing trend afterwards.” This downturn was concomitant with a warming of the globe the IPCC claims was unprecedented over the past one to two millennia, leading the three authors to conclude global warming may actually imply “a possible reduction of hail occurrence.”

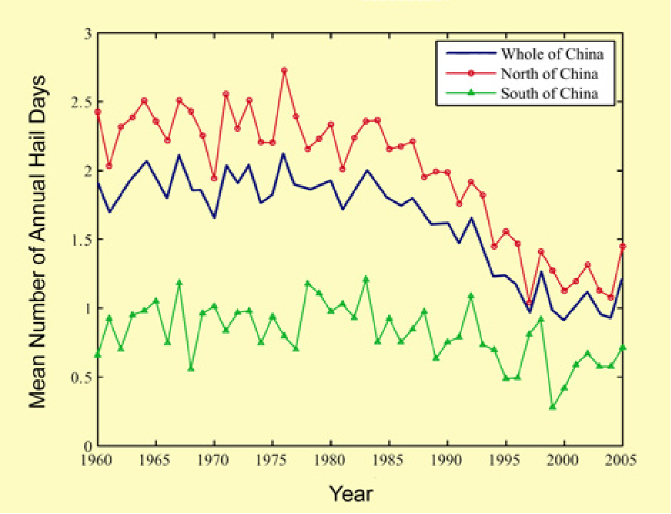

Figure 7.7.3.1. Mean Annual Hail Day variations and trends in northern China, southern China, and the whole of China. Adapted from Xie, B., Zhang, Q., and Wang, Y. 2008. Trends in hail in China during 1960–2005. *Geophysical Research Letters* **35**: 10.1029/2008GL034067.

Recognizing Xie *et al.* (2008) found a “significant decreasing trend of hail frequency in most of China from the early 1980s based on 46 years of data during 1960-2005,” Xie and Zhang (2010) set out to learn whether there also had been any change in another type of extremeness (hailstone size), noting “changes in hail size are also an important aspect of hail climatology." They examined the long-term trend of hail size in four regions of China over the period 1980–2005, using maximum hail diameter data obtained from the Meteorological Administrations of Xinjiang Uygur Autonomous Region (XUAR), Inner Mongolia Autonomous Region (IMAR), Guizhou Province, and Hebei Province.

The researchers found an uptrend in maximum hail diameter in Hebei, a flat trend in XUAR, and a slight downtrend in both Guizhou and IMAR, but "none of the trends is statistically significant."

These results, combined with the other findings presented above, demonstrate global warming, CO_2-induced or otherwise, likely has had nothing to do with the increasing damages caused by extreme weather events in general. It also has had no tendency to increase the occurrence of hail storms, at least in the United States, China, and portions of Poland for which pertinent data have been properly analyzed.

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7.7.4 Tornadoes

According to the latest IPCC report, there is "insufficient evidence" to determine whether small-scale severe weather events such as tornadoes are changing in response to what the IPCC perceives to be an unprecedented rise in both atmospheric CO_2 and temperature of the modern era (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The research reviewed below, however, , strongly suggests changes in CO_2 and temperature have exerted no measurable influence on tornado trends. Because tornadoes often occur in conjunction with other severe storm events, other features of severe storms are frequently mentioned in the studies discussed below.

In a review of "temporal fluctuations in weather and climate extremes that cause economic and human health impacts," Kunkel *et al*. (1999) analyzed empirical data related to historical trends of several different types of extreme weather events and their societal impacts. This work revealed "most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses." However, they found "trends in most related weather and climate extremes do not show comparable increases with time," suggesting "increasing losses are primarily due to increasing vulnerability arising from a variety of societal changes, including a growing population in higher risk coastal areas and large cities, more property subject to damage, and lifestyle and demographic changes subjecting lives and property to greater exposure." Regarding tornado losses, they specifically state "increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors."

Balling and Cerveny (2003) also reviewed the scientific literature to determine what had been learned about severe storms in the United States during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense precipitation, tornadoes, hurricanes, and winter storm activity. They found several scientists had identified an increase in heavy precipitation, but "in other severe storm categories, the trends are downward," just the opposite of what climate models contend should be the case.

Noting "media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe weather events," with these changes implied as being mostly for the worse, Hage (2003) used "previously unexploited written resources such as daily and weekly newspapers and community histories" to establish a database adequate for determining long-term trends of destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) in the prairie provinces of Alberta and Saskatchewan in western Canada over the period 1882 to 2001. Because "sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns," Hage writes, "extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors." The results of these operations are stated quite simply: "All intense storms showed no discernible changes in frequency after 1940.

Changnon (2003) investigated trends in both severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States. He found trends in various weather extremes were mixed, noting "one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms)." Had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

As to why insurance losses rose so rapidly over the past several decades, Changnon reports "the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society's vulnerability." When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events "do not exhibit an upward trend." Changnon emphasizes, "the adjusted loss values for these extremes [do] not indicate a shift due to global warming." These real-world observations, he notes, "do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO_2 levels, that call for weather extremes and storms to increase in frequency and intensity."

Khandekar (2003) briefly reviews what he learned about extreme weather events in Canada while conducting a study of the subject for the government of Alberta. He notes his research led him to conclude "extreme weather events such as heat waves, rain storms, tornadoes, winter blizzards, etc., [were] not increasing anywhere in Canada at [that] time." In addition, he notes a special issue of *Natural Hazards* (Vol. 29, No. 2) concluded much the same thing about other parts of the world, citing a survey article by Robert Balling, who found "no significant increase in overall severe storm activity (hurricanes, thunderstorms/tornadoes, winter blizzards) across the conterminous United States," and the previously cited work of Changnon.

Daoust (2003) catalogued daily tornado frequencies for each county of Missouri (USA) for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state's 115 counties, its six climatic divisions, and the entire state. This work revealed the presence of positive trends in tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant but negative. At the level of the entire state, Daoust reported "for the last 53 years, no long-term trend in tornado days can be found."

Diffenbaugh *et al*. (2008) briefly reviewed what is known about responses of U.S. tornadoes to rising temperatures. On the theoretical side of the issue, they indicate there are competing ideas with regard to whether tornadoes might become more or less frequent and/or severe as the planet warms. On the observational side, there is also much uncertainty about the matter. They write, for example, "the number of tornadoes reported in the United States per year has been increasing steadily (~14 per year) over the past half century," but they note "determining whether this is a robust trend in tornado occurrence is difficult" because "the historical record is both relatively short and non-uniform in space and time." In addition, the increase in yearly tornado numbers runs parallel with the concurrent increase in the country's population, which makes for better geographical coverage and more complete (i.e., numerous) observations.

On the other hand, the three researchers report the number of tornadoes classified as the most damaging (F2–F5 on the Fujita scale) may have truly decreased over the past five decades (1954–2003), as their frequency of occurrence actually runs counter to the trend of the nation's population. The graphs they present show yearly F2–F5 tornado numbers in the latter half of the record period dropping to only about half of what they were during the first half of the record, while corresponding data from the U.S. Southern Great Plains show damaging tornado numbers dropping to only about a third of what they were initially. Nevertheless, Diffenbaugh *et al.* consider the question posed in the title of their paper—Does global warming influence tornado activity?—to be unresolved, stating "determining the actual background occurrence and trend in tornado activity over recent decades will certainly require further development of other analysis approaches."

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7.7.5 Wind

Differences in pressure, or pressure gradients, cause wind. How, then, does wind respond to rising temperatures? Several studies have addressed different aspects of this question in recent years. McPhaden and Zhang (2002), for example, studied surface winds over the Pacific Ocean and the currents they produce in the water below that flow outward from the equator and eventually sink and flow back from both hemispheres to meet and rise near the equator. They discovered over the period 1950–1999, this overturning circulation of the ocean "has been slowing down since the 1970s, causing a decrease in upwelling of about 25% in an equatorial strip between 9°N and 9°S." The scientists say the gradual decline may have been caused by global warming—the opposite of what climate models suggest should happen—but they also note natural variability may just as easily have been the cause of what they observed.

Siegismund and Schrum (2001) investigated wind speed characteristics over the North Sea for the period 1958–1997. They found "the annual mean wind speed for the North Sea shows a rising trend of ~10% during the last 40 years," in harmony with what climate models typically predict. In addition, they determined "since the early 1970s 'strong wind' events are more frequent than in the 1960s," also in harmony with model-based predictions. As for the cause of these phenomena, however, the researchers say their data "may suggest an anthropogenic origin, but this hypothesis can neither be supported nor disproved by analyzing such short time series."

Slonosky *et al.* (2000) analyzed atmospheric surface pressure data from 51 stations located throughout Europe and the eastern North Atlantic over the period 1774–1995, finding atmospheric circulation over Europe was "considerably more variable, with more extreme values in the late 18th and early 19th centuries than in the 20th century." Pirazzoli (2000) studied tide-gauge and meteorological (wind and atmospheric pressure) data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions (storms) and strong surge winds for this region "are becoming less frequent."

Barring and von Storch (2004) analyzed pressure readings for Lund (since 1780) and Stockholm (since 1823) in Sweden to create a record of storminess. They found their proxy time series for storminess were "remarkably stationary in their mean, with little variations on time scales of more than one or two decades." Specifically, they report "the 1860s–70s was a period when the storminess indices showed general higher values," as was the 1980s–1990s, but subsequently, "the indices have returned to close to their long-term mean." Barring and von Storch conclude their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." In fact, during "the entire historical period," they write, storminess was "remarkably stable, with no systematic change and little transient variability."

Contemporaneously, Hanna *et al.* (2004) examined several climatic variables, including air pressure, temperature, precipitation, and sunshine data, over the past century in Iceland, to determine whether there is "possible evidence of recent climatic changes" in that cold island nation. For the period 1820–2002, annual and monthly pressure data exhibited semi-decadal oscillations but no significant upward or downward trend. As for what may be responsible for the oscillations in the data, they mention the likely influence of the Sun, noting a 12-year peak in their spectral analysis of the pressure data is "suggestive of solar activity."

Expanding the solar/pressure link further, Veretenenko *et al.* (2005) examined the potential influence of galactic cosmic rays (GCR) on the long-term variation of North Atlantic sea-level pressure over the period 1874–1995. Comparisons of long-term variations in cold-season (October–March) sea-level pressure with different solar/geophysical indices revealed increasing sea-level pressure coincided with a secular rise in solar/geomagnetic activity accompanied by a decrease in GCR intensity, whereas long-term decreases in sea-level pressure were observed during periods of decreasing solar activity and rising GCR flux. Spectral analysis further supported a link between sea-level pressure, solar/geomagnetic activity, and GCR flux, as similar spectral characteristics (periodicities) were present among all datasets at time scales ranging from approximately 10 to 100 years.

The results of this analysis support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. As to how this relationship works, Veretenenko *et al*. hypothesize GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development.

Gulev and Grigorieva (2004) used the Voluntary Observing Ship wave data of Worley *et al*. (2005) to characterize significant wind-driven wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists report "the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950," which appears to vindicate the IPCC's thoughts on the subject. "However," they continue, "for the period 1885–2002 there is no secular trend in HS in the Atlantic," and "the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002."

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century "is comparable with that for recent decades," and "in the Atlantic it is even higher than during the last 5 decades." In the Atlantic the mean HS of the entire decade of the 1920s is higher than that of any recent decade; and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes us from conclusively proving this latter point. Given such findings, it is clear annual mean wind-driven wave heights over the last decade of the twentieth century were not higher than those that occurred earlier in the century.

McVicar *et al*. (2010) note there has been great interest "in the widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years," citing the work of Roderick *et al*. (2007), McVicar *et al*. (2008), Pryor *et al*. (2009), and Jiang *et al*. (2010). They state this *stilling*, as it has come to be called, is "a key factor in reducing atmospheric evaporative demand," which drives actual evapotranspiration when water availability is not limiting, as in the case of lakes and rivers. In addition, they note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases, as demonstrated by the work of McVicar *et al*. (2007). Increasing wind speeds lead to increases in atmospheric evaporative demand, whereas decreasing wind speeds do the opposite, and both of these changes can be of great significance for people dependent upon water resources derived from mountainous headwater catchments. It would be advantageous to learn how the change in near-surface wind speed with ground elevation may have varied over the last few decades of global warming, since, as the authors note, "over half the global population live in catchments with rivers originating in mountainous regions (Beniston, 2005), with this water supporting about 25% of the global gross domestic product (Barnett *et al*., 2005)."

Defining *u*z as change in wind speed with change in elevation (*u*z = Δu/Δz, where Δu = u2-u1, Δz = z2-z1, and z2 > z1), McVicar *et al*. calculated monthly averages of *u*z based on monthly average *u* data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China and by MeteoSwiss at 37 sites in Switzerland from January 1960 through December 2006. The authors report their research constituted "the first time that long-term trends in *u*z in mountainous regions have been calculated." The seven scientists found, "for both regions *u*z trend results showed that *u* has declined more rapidly at higher than lower elevations." Such a decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations should act to reduce water loss via evaporation from high-altitude catchments in many of the world's mountainous regions, providing more water for people who obtain it from such sources. McVicar *et al*. note the "reductions in wind speed will serve to reduce rates of actual evapotranspiration partially compensating for increases in actual evapotranspiration due to increasing air temperatures."

More recently, Alexander *et al*. (2011) analyzed storminess across the whole of southeast (SE) Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century. According to the four researchers, their results "show strong evidence for a significant reduction in intense wind events across SE Australia over the past century." More specifically, "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease." "In terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Ekman (1999) utilized a sea-level record beginning in 1774 from Stockholm, Sweden to investigate long-term trends in the levels of the Baltic and North Seas and the relationships of these trends to various climatic factors. They determined there had been throughout the 1800s a rapidly decreasing number of dominating winter winds from the northeast. Since such winds typically tend to reduce sea levels at Stockholm, this regime shift led to a gradual increase in the rate of rise of sea level there. Subsequently, the winter winds gradually shifted to where the dominant airflow was from the southwest. Since winds from this direction tend to promote high sea levels at Stockholm, the rate of rise in sea level there continued to increase. The net result of these wind regime changes was thus a continual increase in the rate of rise of sea level at Stockholm over the entire two-century period, resulting in a mean sea-level rise of 1.0 mm/year over the twentieth century. Thus, as the world transitioned from the Little Ice Age to the Modern Warm Period, sea levels around Stockholm rose, not from the melting of polar ice but from a systematic shifting of wind direction.

In another study from Sweden, cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen), were examined by Björck and Clemmensen (2004) for their content of wind-transported clastic material, to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter wind climate in that part of the world. The researchers report, "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," and "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

Björck and Clemmensen also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they state an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)," and they find a period of high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting this period coincides with the Sporer Minimum of AD 1420–1530. They note the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Clarke *et al*. (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, identifying three main phases of wind-induced dune formation: 4,000–3,000 years ago during the long cold interval that preceded the Roman Warm Period; 1,300–900 years ago during the early to middle Medieval Warm Period, but during what they describe as its cooler periods; and 550–250 years ago during the Little Ice Age, again during what they call its cooler periods. In addition, a search of the literature allowed the scientists to identify similar massive wind-induced movements of sand in England, Scotland, Denmark, Portugal, and the Netherlands during these periods of relative coolness. For the most recent of these cool periods, they also note the existence of voluminous historical records that describe many severe North Atlantic wind storms.

Working with insurance industry data, Changnon (2009) analyzed "catastrophes caused solely by high winds" that had had their losses adjusted so as to make them "comparable to current year [2006] values." Although the average monetary loss of each year's catastrophes "had an upward linear trend over time, statistically significant at the 2% level," when the number of each year's catastrophes was considered, it was found "low values occurred in the early years (1952–1966) and in later years (1977–2006)," and "the peak of incidences came during 1977–1991." Changnon reports "the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend."

Two years later in a similar study, Changnon (2011) calculated trends in a number of straight-line wind-related parameters over the period 1950–2006. According to the Illinois State Water Survey researcher, high winds—excluding those associated with hurricanes, tornadoes, snowstorms, blizzards, and heavy rainstorms—are one of the United States' leading types of damage-producing storms. These straight-line windstorms, as they are called, produce annual U.S. property and crop losses totaling $380 million and rank as the nation's sixth-most-damaging type of severe weather.

With respect to whether the global warming of the past half-century has had any significant effect on straight-line windstorm frequency or ferocity, Changnon notes "the distribution of losses over time showed high values in recent years, 1997–2006, and the 55-year distribution had a statistically significant upward trend over time." However, he further describes how a number of adjustments to loss data of the past needed to be made "to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current year values, 2006 in this study." When these adjustments were made, he reports the 55-year time trend "was not up or down." He finds "the national temporal distribution of catastrophic windstorms during 1952–2006 has a flat trend," suggesting, the global warming of the past half-century or so has had no noticeable impact on the net frequency or ferocity of straight-line windstorms in the United States.

The research summarized here suggests the cool nodes of Earth's millennial-scale climatic oscillation are more prone to high wind conditions than are its warm nodes, and the gradual warming of the globe over the past two centuries has probably reduced wind speeds over many portions of the planet, although there may be regional exceptions. In addition, changes in wind speed have implications for a host of other phenomena, from reconstructions of sea-level histories to fluctuations in evaporation and wave heights. Finally, there is some evidence these wind-driven phenomena may be solar-induced.

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7.8 Hurricanes

For many years, nearly all climate model output suggested tropical cyclones (TC) should become both more frequent and more intense as planetary temperatures rise. As a result of such projections, scientists worked to improve the temporal histories of these particular TC characteristics for various ocean basins around the world in an effort to evaluate the plausibility of such projections. In nearly all instances, the research revealed TCs have not been increasing in frequency or magnitude during the era of modern instrumentation and rise of atmospheric CO_2.

As a result of these findings, the IPCC revised its conclusion on hurricanes, stating in its most recent report, "recent re-assessments of tropical cyclone data do not support the [Fourth Assessment Report] conclusions of an increase in the most intense tropical cyclones or an upward trend in the potential destructiveness of all storms since the 1970s. There is low confidence that any reported long-term changes are robust, after accounting for past changes in observing capabilities."

Not willing to disavow the model projection fully, the IPCC adds, "over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust" (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, despite the vast array of observational data that do not support the model projections, the IPCC continues to project future increases in certain TC parameters for the globe (increase in TC intensity) and for individual ocean basins (increase in the number of intense storms):

> Projections for the 21st century indicate that it is likely that the global frequency of tropical

> cyclones will either decrease or remain essentially unchanged, concurrent with a likely global increase in both tropical cyclone maximum wind speed and rainfall rates, but there is lower confidence in region-specific projections. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 59).
>
> … it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates … It is more likely than not that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 62).

In light of the IPCCs continued claims regarding hurricanes, Section 7.10 reviews the scientific literature to present a detailed examination of what has been learned with respect to such storms in various ocean basins across the globe. The results of that examination reveal real-world data do not support, and in fact essentially invalidate, the model claims. Global warming, whether CO_2-induced or natural, is likely to have no measurable influence on the frequency or intensity of tropical cyclones.

7.8.1 Atlantic Ocean

Data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Atlantic Ocean.

7.8.1.1 Frequency

7.8.1.1.1 The Past Century

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what the IPCC describes as unprecedented global warming?

In an early attempt to answer this question, Bove *et al.* (1998) examined the characteristics of all recorded landfalling U.S. Gulf Coast hurricanes—defined as those whose eyes made landfall between Cape Sable, Florida and Brownsville, Texas—from 1896 to 1995. They found the first half of this period saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade, and the same was true for intense hurricanes of category 3 or more on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes both trended downward from 1966 to the end of the period investigated, with the decade 1986–1995 exhibiting the fewest intense hurricanes of the century. The three researchers conclude, “fears of increased hurricane activity in the Gulf of Mexico are premature.”

Noting the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but during the preceding four years (1991–1994) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al.* (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. They found “perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region.” They also note, “in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea level pressure, abnormally warm ocean waters, and very humid values of total precipitable water.”

The enhanced activity of the 1995 Atlantic hurricane season also may have been affected by the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Most important, perhaps, was what Landsea *et al.* called the “dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions,” which contributed to what they described as “the dramatic reversal” of weather characteristics “which dominated during the [prior] four hurricane seasons.”

The four researchers note, “Some have asked whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic ‘greenhouse’ gases.” They concluded “such an interpretation is not warranted,” because the factors noted above seem sufficient to explain the observations. “Additionally,” they write, “Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean intensity of all named storms over the past few decades," and "this holds true even with the inclusion of 1995's Atlantic hurricane season."

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al.* (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944–1996, decreasing trends were found for the total number of hurricanes, the number of intense hurricanes, the annual number of hurricane days, the maximum attained wind speed of all hurricane storms averaged over the course of a year, and the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they report the total number of Atlantic hurricanes making landfall in the United States decreased over the 1899–1996 time period, and normalized trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of $728 million per decade.

Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States during the period 1935–1998. They found "a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of -0.011 ± 0.0086 storms per year." They expressly note "the estimated trend slope is negative," meaning the yearly number of such storms is decreasing, just the opposite of what they described as the "frequent hypothesis ... that global warming is causing increased storm activity." Their statistical analysis indicates "the trend slope is not significantly different from zero."

Easterling *et al.* (2000) point out the mean temperature of the globe rose by about 0.6°C over the past century. They looked for possible impacts of this phenomenon on extreme weather events, which if found to be increasing, "would add to the body of evidence that there is a discernible human affect on the climate." Their search revealed few changes of significance, although they did determine "the number of intense and landfalling Atlantic hurricanes has declined."

Balling and Cerveny (2003) wrote, "many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones," but they note empirical studies had failed to reveal any such relationships. They also note "some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events," and these relationships have not been thoroughly studied with historical real-world data.

The two Arizona State University climatologists constructed a daily database of tropical storms that occurred in the Caribbean Sea, Gulf of Mexico, and western North Atlantic Ocean over the period 1950–2002, generating "a variety of parameters dealing with duration, timing, and location of storm season," after which they tested for trends in these characteristics, attempting to explain the observed variances in the variables using regional, hemispheric, and global temperatures. They "found no trends related to timing and duration of the hurricane season and geographic position of storms in the Caribbean Sea, Gulf of Mexico and tropical sector of the western North Atlantic Ocean." They also "could find no significant trends in these variables and generally no association with them and the local ocean, hemispheric, and global temperatures."

Elsner *et al.* (2004) conducted a changepoint analysis of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the twentieth century. This technique, they write, "quantitatively identifies temporal shifts in the mean value of the observations." Their work revealed "major North Atlantic hurricanes have become more frequent since 1995," but at "a level reminiscent of the 1940s and 1950s." That appears to be an overstatement of their findings; their data indicate the mean annual hurricane count for the seven-year period 1995–2001 was 3.86, while the mean count for the 14-year period 1948–1961 was 4.14. They also report, "in general, twentieth-century U.S. hurricane activity shows no abrupt shifts," noting there was an exception over Florida, "where activity decreased during the early 1950s and again during the late 1960s." They also found "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

Elsner *et al.*'s work contradicts the claim that global warming leads to more intense hurricane activity. North Atlantic hurricane activity did not increase over the twentieth century, during which the IPCC says Earth experienced a temperature increase unprecedented over the past two millennia. Moreover, hurricane activity also did not increase, and in fact decreased, in response to the more sporadic warming associated with periodic El Niño conditions.

Virmani and Weisberg (2006) report "the 2005 hurricane season saw an unprecedented number of named tropical storms since records began in 1851." Moreover, they note it followed "on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path." They wondered whether the increased hurricane activity occurred in response to recent global warming or if it bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

The two researchers determined "latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea level pressure," which "resulted in anomalously high sea surface temperatures" that "contributed to earlier and more intense hurricanes in 2005." They note "these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998." In addition, they found no "clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation." It would appear the 2005 hurricane season was not as unusual as many people have made it out to be, and there is no compelling reason to ascribe whatever degree of uniqueness it may have possessed to recent global warming.

Mann and Emanuel (2006) used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871–2005, and Holland and Webster (2007) analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both papers linked these changes to anthropogenic greenhouse warming.

In a compelling rebuttal of these conclusions, Landsea (2007) cited a number of possible biases in the cyclone frequency trends derived in the two studies, concluding "improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones."

Parisi and Lund (2008) calculated return periods of Atlantic-basin U.S. landfalling hurricanes based on "historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques" for each of the categories (1–5) of the Saffir-Simpson Hurricane Scale. Return periods, in ascending Saffir-Simpson Scale category order, were 0.9 years for category 1, 1.3 years for category 2, 2.0 years for category 3, 4.7 years for category 4, and 23.1 years for category 5 hurricanes. In addition, the two researchers reported corresponding non-encounter probabilities in any one hurricane season were calculated to be (category 1) 0.17, (category 2) 0.37, (category 3) 0.55, (category 4) 0.78, and (category 5) 0.95. The hypothesis that U.S. hurricane strike frequencies are "increasing in time"—which is often stated as fact—is "statistically rejected," they conclude.

Chylek and Lesins (2008) applied "simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity and other features of interest." Using a hurricane activity index that integrates hurricane numbers, durations, and strengths, the two researchers report discovering "a quasi-periodic behavior with a period around 60 years superimposed upon a linearly increasing background." However, they note "the linearly increasing background is significantly reduced or removed when various corrections were applied for hurricane undercounting in the early portion of the record." Further noting "the last minimum in hurricane activity occurred around 1980," Chylek and Lesins compared the two 28-year-long periods on either side of this date, finding "a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification." They conclude, "if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60-year quasi-periodic cycle."

Klotzbach and Gray (2008) employed sea surface temperature (SST) data for the far North Atlantic (50–60°N, 50–10°W) and sea-level pressure (SLP) data for the North Atlantic (0-50°N, 70-10°W) to construct an index of the Atlantic Multidecadal Oscillation (AMO), which they defined as the difference between the standardized SST and SLP anomalies (SST-SLP) for the hurricane season of June–November, and which they evaluated for the period 1878–2006. They compared their results, to which they applied a 1-2-3-

2-1 filter, with a number of hurricane properties.

Klotzbach and Gray's analysis revealed the existence of three positive and two negative AMO phases over the period of their study, as illustrated in Figure 7.8.1.1.1.

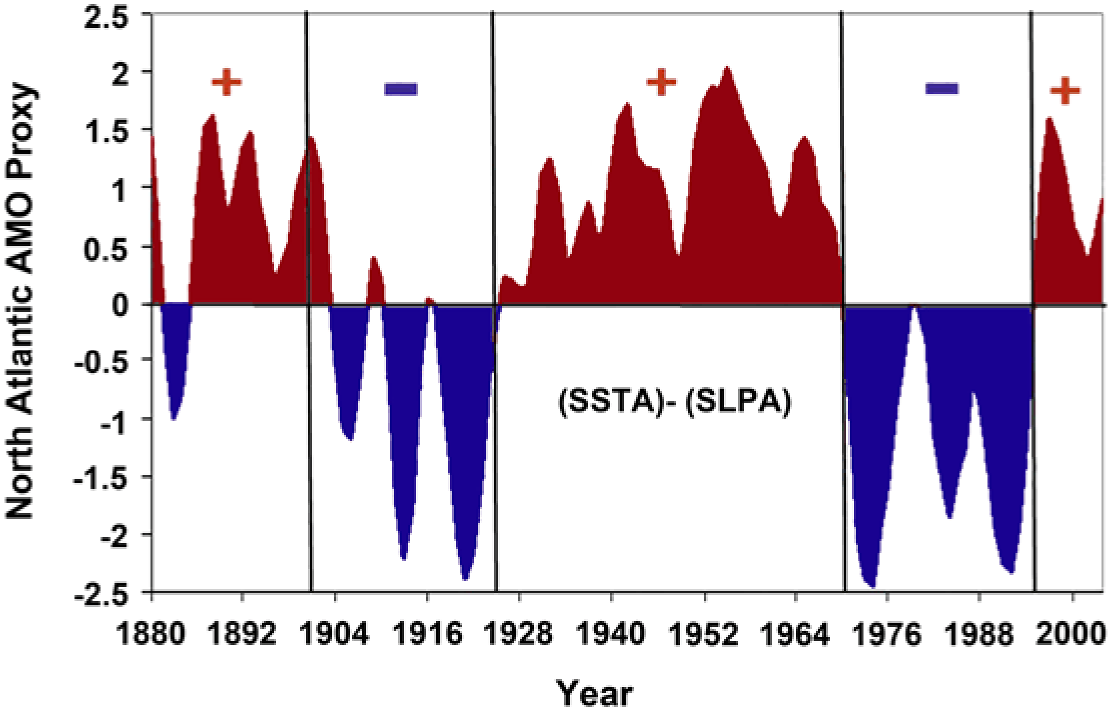

Figure 7.8.1.1.1. North Atlantic AMO Index. Adapted from Klotzbach, P.J. and Gray, W.M. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate* **21**: 3929-3935.

In comparing annually averaged results for tropical cyclone characteristics between the positive and negative AMO phases indicated in the figure, it can be calculated from the tropical cyclone data of the authors that the positive-AMO-phase to negative-AMO-phase ratios of hurricane numbers, hurricane days, major hurricane numbers, and major hurricane days were 1.53, 1.89, 2.00, and 2.46, respectively, over the period studied. For the 20 most positive and 20 most negative AMO years, those ratios, in the same order, were 1.73, 2.41, 2.80, and 4.94. Such calculations demonstrate the North Atlantic AMO is tremendously important to hurricane genesis and development, and this striking natural variability makes it extremely difficult to determine whether there is any long-term trend in the tropical cyclone data that might be attributable to twentieth century global warming.

Zeng *et al.* (2009) "synthesized field measurements, satellite image analyses, and empirical models to evaluate forest and carbon cycle impacts for historical tropical cyclones from 1851 to 2000 over the continental U.S." They found greater forest impacts and biomass loss between 1851 and 1900 from hurricane activity than during the twentieth century. On average, the authors found "147 million trees were affected each year between 1851 and 1900," which led to "a 79-Tg annual biomass loss." Average annual forest impact and biomass loss between 1900 and 2000 "were 72 million trees and 39 Tg, which were only half of the impacts before 1900." The authors say these results are in "accordance with historical records showing that Atlantic tropical cyclones were more active during the period from 1870 to 1900." They also note the amount of carbon released from the downed and damaged trees "reached a maximum value in 1896, after which it continuously decreased until 1978," when it leveled off for the remaining two decades of the twentieth century.

Hagen and Landsea (2012) point out "previous studies state that there has been an increase in the number of intense hurricanes and [they] attribute this increase to anthropogenic global warming," but "other studies claim that the apparent increased hurricane activity is an artifact of better observational capabilities and improved technology for detecting these intense hurricanes." They focused their research on the ten most recent Category 5 hurricanes known to have occurred in the Atlantic Ocean, from Hurricane Andrew in 1992 to Hurricane Felix of 2007. Placing these ten hurricanes into the context of the technology available from 1944 to 1953—the first decade of aircraft reconnaissance—they determined how many of these Category 5 hurricanes likely would have been recorded as Category 5 if they had occurred during the earlier period, using only the observations likely to have been available with then-existing technology and observational networks.

The two U.S. researchers report "there are likely to have been several Category 4 and 5 hurricanes misclassified as being weaker prior to the satellite era." For example, "if the ten most recent Category 5 hurricanes occurred during the late-1940s period, only two of them would be considered Category 5 hurricanes (and three of ten for the early-1950s period)." In addition, "three recent Category 4 hurricanes were identified that would likely not have been counted as major hurricanes if they had occurred during the late 1940s/1950s." Hagen and Landsea conclude, "counts of Category 4 and 5 hurricanes (at least through 1953 and likely beyond that year) are not nearly as reliable as they are today." They further conclude "future studies that discuss frequency trends of Atlantic basin Category 4 and 5 hurricanes must take into account the undercount biases that existed prior to the geostationary satellite era due to the inability to observe these extreme conditions."

Villarini *et al*. (2011) used the statistical model developed by Villarini *et al*. (2010), in which "the frequency of North Atlantic tropical storms is modeled by a conditional Poisson distribution with a rate of occurrence parameter that is a function of tropical Atlantic and mean tropical sea surface temperatures (SSTs)," to examine "the impact of different climate models and climate change scenarios on North Atlantic and U.S. landfalling tropical storm activity," and reconcile "differing model projections of changes in the frequency of North Atlantic tropical storms in a warmer climate."

The five researchers report their results "do not support the notion of large increases in tropical storm frequency in the North Atlantic basin over the twenty-first century in response to increasing greenhouse gases." They also note "the disagreement among published results concerning increasing or decreasing North Atlantic tropical storm trends in a warmer climate can be largely explained (close to half of the variance) in terms of the different SST projections (Atlantic minus tropical mean) of the different climate model projections."

They also find, "for the SRES A1B scenario and 24 climate models, over the twenty-first century there is a large spread among projected trends in tropical storm activity in the North Atlantic basin, with a mean of -0.83 tropical storm per century and a standard deviation of 2.48 tropical storms per century." And with respect to U.S. land-falling tropical storms, they state, "results based on 7 climate models point to a statistically significant increasing trend, while 6 point to a decreasing trend," suggesting the models are inconsistent in projecting what will happen over the current century. Villarini *et al.* (2011) conclude, among other things, "there is a considerable level of uncertainty in climate change projections that will remain effectively 'irreducible,' as no current prospects exist for skillful century-scale predictions of unforced climate variability."

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7.8.1.1.2 The Past Few Centuries

Has the warming of the past century, which rescued the world from the extreme cold of the Little Ice Age, led to the formation of more numerous Atlantic Basin tropical storms and hurricanes? Several studies have broached this question with sufficiently long data records to provide reliable answers.

Elsner *et al*. (2000) provided a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales, and they presented data on major hurricane occurrences in 50-year intervals for Bermuda, Jamaica, and Puerto Rico. These data reveal hurricanes occurred at far lower frequencies in the last half of the twentieth century than they did in the preceding five 50-year periods at all three of the locations studied. From 1701 to 1850, for example, when Earth was in the grip of the Little Ice Age, major hurricane frequency was 2.77 times greater at Bermuda, Jamaica, and Puerto Rico than it was from 1951 to 1998. From 1851 to 1950, when the planet was in transition from the Little Ice Age to current conditions, the three locations experienced a mean hurricane frequency 2.15 times greater than what they experienced from 1951 to 1998.

Such findings for the Caribbean Sea were echoed by Elsner (2008) in his summary of the *International Summit on Hurricanes and Climate Change* held in May 2007. He states paleotempestology—which he defines as the study of prehistoric storms based on geological and biological evidence—indicates the presence of more hurricanes in the northeastern Caribbean Sea “during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today.” He goes on to say his work provides evidence that “today’s warmth is not needed for increased storminess.”

In another multicentury study, Boose *et al*. (2001) used historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They find “no clear century-scale trend in the number of major hurricanes.” At lower damage levels, fewer hurricanes were recorded in the seventeenth and eighteenth centuries than in the nineteenth and twentieth centuries, but the three researchers conclude “this difference is probably the result of improvements in meteorological observations and records since the early 19th century.” With the better records of the past 200 years, it is clear the cooler nineteenth century had five of the highest-damage storms, whereas the warmer twentieth century had only one such storm.

Nyberg *et al*. (2007) developed a history of major (Category 3–5) Atlantic hurricanes over the past 270 years based on proxy records of vertical wind shear and sea surface temperature derived from corals and a marine sediment core. Wind shear and SST are the primary controlling forces for the formation of major hurricanes in the region west of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10°N and 20°N, where 85% of all major hurricanes and 60% of all non-major hurricanes and tropical storms of the Atlantic are formed.

The researchers discovered the average frequency of major Atlantic hurricanes "decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s." They note "a gradual downward trend is evident from an average of ~4.1 (1775–1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s," and "the current active phase (1995–2005) is unexceptional compared to the other high-activity periods of ~1756–1774, 1780–1785, 1801–1812, 1840–1850, 1873–1890 and 1928–1933." They conclude the recent ratcheting up of Atlantic major hurricane activity appears to be simply "a recovery to normal hurricane activity." In a commentary on Nyberg *et al.*'s paper, Elsner (2007) stated "the assumption that hurricanes are simply passive responders to climate change should be challenged," which Nyberg *et al.* do convincingly.

Also noting "global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean," with the implication that "a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State," Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005.

The work revealed "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and of these storms, "14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms." For Long Island, he reports "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." He finds storm activity was greatest in both the late nineteenth century and the late twentieth century, and "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century." Vermette concludes, "rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century."

Mock (2008) developed a "unique documentary reconstruction of tropical cyclones for Louisiana, USA, that extends continuously back to 1799 for tropical cyclones and to 1779 for hurricanes." Mock says this record, derived from daily newspaper accounts, private diaries, plantation diaries, journals, letters, and ship records and augmented "with the North Atlantic hurricane database as it pertains to all Louisiana tropical cyclones up through 2007," is "the longest continuous tropical cyclone reconstruction conducted to date for the United States Gulf Coast." The record reveals "the 1820s/early 1830s and the early 1860s are the most active periods for the entire record."

The University of South Carolina researcher says "the modern records which cover just a little over a hundred years [are] too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude." He states, "if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [those storms] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005."

Chenoweth and Divine (2008) examined newspaper accounts, ships' logbooks, meteorological journals, and other documents to reconstruct a history of tropical cyclones passing through the 61.5°W meridian between the coast of South America (~9.7°N) and 25.0°N over the period 1690–2007, which they describe as "the longest and most complete record for any area of the world." The two authors found "no evidence of statistically significant trend in the number of tropical cyclones passing through the region on any time scale." They also note "hurricane frequency is down about 20% in the 20th century compared to earlier centuries," and "this decline is consistent with the 20th century observed record of decreasing hurricane landfall rates in the U.S. (Landsea *et al.*, 1999; Elsner *et al.*, 2004) and proxy reconstruction of higher tropical cyclone frequency in Puerto Rico before the 20th century (Nyberg *et al.*, 2007), as well as model-simulated small changes in Atlantic basin tropical cyclone numbers in a doubled CO_2 environment (Emanuel *et al.*, 2008; Knutson *et al.*, 2008)." In addition, they report "the period 1968–1977 was probably the most inactive period since the islands were settled in the 1620s and 1630s," which, in their words, "supports the results of Nyberg *et al*. (2007) of unprecedented low frequency of major hurricanes in the 1970s and 1980s."

Following up on their work four years later, Chenoweth and Divine (2012) examined the records employed in their earlier paper in more detail, determining "the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian." Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends.

Chenoweth and Divine report their record of tropical cyclone activity "reveals no trends in LACE in the best-sampled regions for the past 320 years," and "even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or LACE," noting these results are similar to those reported earlier by them (Chenoweth and Divine, 2008) on tropical cyclone counts. In addition, they indicate LACE along the 61.5°W meridian is "highly correlated" with Atlantic-Basin-wide ACE.

Wang and Lee (2008) used the "improved extended reconstructed" sea surface temperature (SST) data described by Smith and Reynolds (2004) for the period 1854–2006 to examine historical temperature changes over the global ocean, after which they regressed vertical wind shear—"calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data"—onto a temporal variation of global warming defined by the SST data. They discovered warming of the surface of the global ocean is typically associated with a secular increase of tropospheric vertical wind shear in the main development region (MDR) for Atlantic hurricanes, and the long-term increased wind shear of that region has coincided with a weak but robust downward trend in U.S. landfalling hurricanes. However, this relationship has a pattern to it, whereby local ocean warming in the Atlantic MDR reduces the vertical wind shear there, whereas "warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes."

The two researchers conclude "the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes" to date, "warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes." As for the future, they write, "whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans."

Vecchi and Knutson (2008) point out "there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency." They derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) missed by the observing system in the pre-satellite era (1878–1965), after which they analyzed trends of reconstructed TC numbers and duration over various time periods and assessed whether those trends might have been related to trends in sea surface temperature over the main development region of North Atlantic TCs.

Vecchi and Knutson found "the estimated trend for 1900–2006 is highly significant (+~4.2 storms century^{-1})" but "strongly influenced by a minimum in 1910–30, perhaps artificially enhancing significance." When using their base case adjustment for missed TCs and considering the entire 1878–2006 record, they find the trend in the number of TCs is only "weakly positive" and "not statistically significant," and they note the trend in average TC duration over the 1878–2006 period "is negative and highly significant."

Similar shortcomings in the observational record have been reported by other researchers. Landsea *et al*. (2010) note "records of Atlantic basin tropical cyclones (TCs) since the late nineteenth century indicate a very large upward trend in storm frequency," and they state this increase in documented TCs "has been previously interpreted as resulting from anthropogenic climate change." The note "improvements in observing and recording practices provide an alternative interpretation for these changes" and report "recent studies suggest that the number of potentially missed TCs is sufficient to explain a large part of the recorded increase in TC counts."

Landsea *et al*. explored the influence of another factor—TC duration—on observed changes in TC frequency, working with the widely used Atlantic hurricane database known as HURDAT. They found the occurrence of short-lived storms of two days duration or less had increased dramatically, from less than one per year in the late nineteenth and early twentieth centuries to about five per year since about AD 2000, whereas numbers of medium- to long-lived storms had increased "little, if at all." They conclude the previously documented increase in total TC frequency since the late nineteenth century in the database was "primarily due to an increase in very short-lived TCs."

Landsea *et al*. next conducted a sampling study based on the distribution of ship observations, which provided quantitative estimates of the frequency of missed TCs with durations exceeding two days. Upon adding the estimated numbers of missed TCs to the time series of moderate and long-lived Atlantic TCs, they found "neither time series exhibits a significant trend since the late nineteenth century."

Landsea *et al*. conclude sub-sampling of TCs back in time will artificially introduce increases in a wide array of TC characteristics, including "frequency of hurricanes and major hurricanes, duration of TCs, length of season, peak intensity, and integrated TC measures [like Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI)]," which they say "should not be used directly from HURDAT for climate variability and change studies without consideration of, or quantitatively accounting for, how observational network alterations are affecting these statistics."

Vecchi and Knutson (2011) conducted a new analysis of the characteristics of Atlantic hurricanes whose peak winds exceeded 33 m/s for the period 1878–2008, based on the HURDAT database, developing a new estimate of the number of hurricanes that occurred in the pre-satellite era (1878–1965) based on analyses of TC storm tracks and the geographical distribution of the tracks of the ships that reported TC encounters. The two researchers report "both the adjusted and unadjusted basin-wide hurricane data indicate the existence of strong interannual and decadal swings." Although "existing records of Atlantic hurricanes show a substantial increase since the late 1800s," their analysis suggests "this increase could have been due to increased observational capability." They write, "after adjusting for an estimated number of 'missed' hurricanes (including hurricanes that likely would have been miss-classified as tropical storms), the secular change since the late-nineteenth century in Atlantic hurricane frequency is nominally negative—though not statistically significant." The two researchers from NOAA's Geophysical Fluid Dynamics Laboratory say their results "do not support the hypothesis that the warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase."

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7.8.1.1.3 The Past Few Millennia

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? Several studies have examined thousand-year reconstructions of the region's intense hurricane activity.

Liu and Fearn (1993) analyzed sediment cores retrieved from the center of Lake Shelby in Alabama (USA) to determine the history of intense (Category 4 and 5) hurricane activity over the past 3,500 years. Over the period of their study, "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years." The researchers report the last of these hurricane strikes occurred about 700 years ago. It would therefore appear twentieth century global warming has not accelerated the occurrence of such severe storm activity.

Seven years later, Liu and Fern (2000) studied 16 sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico over the past 7,000 years. Twelve major hurricanes of Category 4 or 5 intensity were found to have struck the Western Lake region during this period. Eleven of the 12 events occurred during a 2,400-year period between 1,000 and 3,400 years ago. Only one major hurricane strike was recorded between 0 and 1,000 years ago, and no major hurricane strikes were recorded between 3,400 and 7,000 years ago.

The two researchers say a probable explanation for the "remarkable increase in hurricane frequency and intensity" that affected the Florida Panhandle and Gulf Coast after 1,400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift south and the Bermuda High southwest of their earlier Holocene positions, such as would be expected with global cooling. They note, "paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime."

Donnelly and Woodruff (2007) state "it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones," citing the studies of Emanuel (2005) and Webster *et al*. (2005). Al Gore expressed a similar view in his 21 March 2007 testimony to the U.S. Senate's Environment & Public Works Committee. Cognizant of the need to consider a longer record of the frequency of occurrence of intense hurricanes than that used by Emanuel and Webster *et al*., Donnelly and Woodruff developed "a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls."

The two researchers from the Woods Hole Oceanographic Institution detected three major intervals of intense hurricane strikes: one between 5,400 and 3,600 calendar years before present (yr BP, where "present" is AD 1950), one between 2,500 and 1,000 yr BP, and one after 250 yr BP. They also report coral-based sea surface temperature (SST) data from Puerto Rico "indicate that mean annual Little Ice Age (250–135 yr BP or AD 1700–1815) SSTs were 2–3°C cooler than they are now," and they state "an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766–1780 was one of the most active intervals in the period between 1500 and 1800 (Garcia-Herrera *et al*., 2005), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation (Gray *et al*., 2004)."

Donnelly and Woodruff conclude "the

information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia." The two researchers write, "studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al*., 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development."

Wallace *et al*. (2010) collected a total of 37 sediment cores along eight transects within Laguna Madre, an elongated water body located behind the narrow low-elevation barrier that is Texas, USA's South Padre Island, constructing a detailed history of intense hurricane strikes from 5,300 to 900 years before present (BP). They report "there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval," i.e., 5.300–900 yr BP, "implying no direct link between changing climate conditions and annual hurricane impact probability." In addition, they say "there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time."

In discussing their findings, as well as the similar results obtained by others for Western Lake, Florida, and Lake Shelby, Alabama, the two Rice University (Houston, Texas, USA) researchers say current rates of intense hurricane impacts "do not seem unprecedented when compared to intense strikes over the past 5000 years," and "similar probabilities in high-intensity hurricane strikes for the eastern and western Gulf of Mexico do not show any clear-cut out-of-phase relationship that would enlighten us as to climate controls on storm pathways."

Similarly noting "the brief observational record is inadequate for characterizing natural variability in hurricane activity occurring on longer than multi-decadal timescales," Lane *et al*. (2011) sought a means of characterizing hurricane activity prior to the period of modern measurement and historical record-keeping, because "the manner in which tropical cyclone activity and climate interact has critical implications for society and is not well understood." They developed a 4,500-year record of intense hurricane-induced storm surges based on data obtained from "a nearly circular, 200-m-diameter cover-collapse sinkhole (Mullet Pond: 29°55.520'N, 84°20.275'W) that is located on Bald Point near Apalachee Bay, Florida, USA," where "recent deposition of sand layers in the upper sediments of the pond was found to be contemporaneous with significant, historic storm surges at the site modeled using SLOSH and the Best Track, post-1851 AD dataset"; "paleohurricane deposits were identified by sand content and dated using radiocarbon-based age models"; and "marine-indicative foraminifera, some originating at least 5 km offshore, were present in several modern and ancient storm deposits."

The four researchers' reconstructed record of intense hurricanes revealed the frequency of these "high-magnitude" events "peaked near 6 storms per century between 2800 and 2300 years ago." The record suggests intense hurricanes were "relatively rare" with "about 0–3 storms per century occurring between 1900 and 1600 years ago," after which these super-storms exhibited a marked decline, which "began around 600 years ago" and has persisted through the present with "below average frequency over the last 150 years when compared to the preceding five millennia."

Over the past century and a half of increasing fossil fuel utilization and atmospheric CO_2 buildup, the frequency of the most intense category of hurricanes in the Northeastern Gulf of Mexico has been lower than it was over the prior five millennia, which speaks volumes about the claim that continued anthropogenic CO_2 emissions will lead to more frequent super cyclones and hurricanes.

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7.8.1.2 Intensity

Setting the stage for a discussion of the effects of CO_2-induced global warming on Atlantic Ocean hurricane intensity, Free *et al.* (2004) note "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al.*, 1998; Knutson *et al.*, 1998)," but "because the predicted increase in intensity for doubled CO_2 is only 5%–20%, changes over the past 50 years would likely be less than 2%—too small to be detected easily." In addition, they say "studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al.*, 1996; Henderson-Sellers *et al.*, 1998; Solow and Moore, 2002)." Several studies have found yearly hurricane numbers to decline as temperatures rise (see Section 7.10.1.1).

Free *et al.* look not for increases in hurricane intensity, but for increases in potential hurricane intensity, because, as they describe it, "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity." They analyzed radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans and compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. Their results "show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." In addition, between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

In the following year, some important new studies prompted a reissuing of the claim that warming enhances tropical cyclone intensity (Emanuel, 2005; Webster *et al.*, 2005), but a new review of the subject once again cast doubt on this contention. Pielke *et al.* (2005) begin their discussion by noting "globally there has been no increase in tropical cyclone frequency over at least the past several decades," citing the studies of Lander and Guard (1998), Elsner and Kocher (2000), and Webster *et al.* (2005). Furthermore, they note research on possible future changes in hurricane frequency due to global warming has produced studies that "give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to base any projections about the future."

With respect to hurricane intensity, Pielke *et al.* note Emanuel (2005) claimed to have found "a very substantial upward trend in power dissipation (i.e., the sum over the life-time of the storm of the maximum wind speed cubed) in the North Atlantic and western North Pacific," but "other studies that have addressed tropical cyclone intensity variations (Landsea *et al.*, 1999; Chan and Liu, 2004) show no significant secular trends during the decades of reliable records." In addition, Pielke *et al.* point out early theoretical work by Emanuel (1987) "suggested an increase of about 10% in wind speed for a 2°C increase in tropical sea surface temperature," but more recent work by Knutson and Tuleya (2004) points to only a 5% increase in hurricane windspeeds by 2080, and Michaels *et al.* (2005) conclude even this projection is likely twice as great as it should be.

Perhaps of greatest significance to the prediction of future hurricanes and the destruction they may cause is the nature and degree of human occupation of exposed coastal areas. By 2050, for example, Pielke *et al.* report "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between \$22 and \$60 of increase in damage due to population growth and wealth," citing the findings of Pielke *et al.* (2000). They state, without equivocation, "the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms."

Pielke *et al.* note many continue to claim a significant hurricane–global warming connection for the purpose of advocating anthropogenic CO_2 emissions reductions that "simply will not be effective with respect to addressing future hurricane impacts," additionally noting "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

In a subsequent analysis of Emanuel's (2005) and Webster *et al.*'s (2005) claims that "rising sea surface temperatures (SSTs) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas concentrations," Michaels *et al.* (2006) used weekly averaged 1° latitude by 1° longitude SST data together with hurricane track data of the National Hurricane Center, which provide hurricane-center locations (latitude and longitude in tenths of a degree) and maximum one-minute surface wind speeds (both at six-hour intervals) for all tropical storms and hurricanes in the Atlantic basin that occurred between 1982 (when the SST data set begins) through 2005. Plotting maximum cyclone wind speed against the maximum SST that occurred prior to (or concurrent with) the maximum wind speed of each of the 270 Atlantic tropical cyclones of their study period, they found for each 1°C increase in SST between 21.5°C and 28.25°C, the maximum wind speed attained by Atlantic basin cyclones rises, in the mean, by 2.8 m/s, and thereafter, as SSTs rise still further, the first Category-3-or-greater storms begin to appear. However, they report, "there is no significant relationship between SST and maximum winds at SST exceeding 28.25°C."

Michaels *et al.* conclude, "while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones." The comparison of SSTs actually encountered by individual storms performed by Michaels *et al.*—as opposed to the comparisons of Emanuel (2005) and Webster *et al.* (2005), which utilized basin-wide averaged monthly or seasonal SSTs—refutes the idea that anthropogenic activity has detectably influenced the severity of Atlantic basin hurricanes over the past quarter-century.

Balling and Cerveny (2006) examined temporal patterns in the frequency of intense tropical cyclones (TCs), the rates of rapid intensification of TCs, and the average rate of intensification of hurricanes in the North Atlantic Basin, including the tropical and subtropical North Atlantic, Caribbean Sea, and Gulf of Mexico, where they say there was "a highly statistically significant warming of 0.12°C decade^{-1} over the period 1970–2003 ... based on linear regression analysis and confirmed by a variety of other popular trend identification techniques." They found "no increase in a variety of TC intensification indices," and "TC intensification and/or hurricane intensification rates ... are not explained by current month or antecedent sea surface temperatures (despite observed surface warming over the study period)." Thus they conclude, "while some researchers have hypothesized that increases in long-term sea surface temperature may lead to marked increases in TC storm intensity, our findings demonstrate that various indicators of TC intensification show no significant trend over the recent three decades."

Klotzbach and Gray (2006) note still other papers question the validity of the findings of Emanuel (2005) and Webster *et al.* (2005) "due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea, 2005)." "While major hurricane activity in the Atlantic has shown a large increase since 1995," they note, "global tropical-cyclone activity, as measured by the accumulated cyclone energy index, has decreased slightly during the past 16 years (Klotzbach, 2006)." They "attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal mode and strength of the Atlantic Ocean thermohaline circulation." They note, "historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25–30 years (typical period ~50–60 years; Gray *et al.*, 1997; Latif *et al.*, 2004)," and "since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15–20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity," demonstrating the science of this subject is far from settled.

Vecchi and Soden (2007a) explored twenty-first century projected changes in vertical wind shear (VS) over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions scenario A1B (atmospheric CO_2 stabilization at 720 ppm by 2100) of the Intergovernmental Panel on Climate Change's *Fourth Assessment Report*, where VS is defined as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa, and where changes are computed between the two 20-year periods 2001–2020 and 2081–2100. The 18-model mean result indicated a prominent increase in VS over the topical Atlantic and East Pacific (10°N–25°N). Noting "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," the two researchers state the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century." They further note, "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America." Consequently, and in addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes (Donnelly and Woodruff, 2007; Nyberg *et al.*, 2007), there is now considerable up-to-date model-based evidence for that conclusion.

In a second, closely related paper, Vecchi and Soden (2007b) used climate models and observational reconstructions "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They found "changes in local sea surface temperature are inadequate for characterizing even the sign of changes in potential intensity." Instead, they report "long-term changes in potential intensity are closely related to the regional structure of warming," such that "regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa."

Using this relationship to reconstruct changes in potential intensity over the twentieth century, based on observational reconstructions of sea surface temperature, they found "even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably peaked in the 1930s and 1950s," noting "recent values are near the historical average." The two scientists concluded the response of tropical cyclone activity to natural climate variations "may be larger than the response to the more uniform patterns of greenhouse-gas-induced warming."

Latif *et al.* (2007) analyzed the 1851–2005 history of Accumulated Cyclone Energy or ACE Index for the Atlantic basin. This parameter "takes into account the number, strength and duration of all tropical storms in a season." They then "analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870–2003."

With respect to the first part of their study, they report "the ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but no sustained long-term trend." With respect to the second part of their study, they report "a clear warming trend is seen in the tropical North Atlantic sea surface temperature," but this warming trend "does not seem to influence the tropical storm activity."

This state of affairs seemed puzzling at first, because a warming of the tropical North Atlantic is known to reduce vertical wind shear there and thus promote the development of tropical storms. However, Latif *et al.*'s modeling work revealed a warming of the tropical Pacific enhances the vertical wind shear over the Atlantic, as does a warming of the tropical Indian Ocean. Consequently, they learned "the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic," and "apparently, the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity [has] remained rather stable and mostly within the range of the natural multidecadal variability."

A striking exception occurred in 2005 when, the researchers report, "the tropical North Atlantic warmed more rapidly than the Indo-Pacific," which reduced vertical wind shear over the North Atlantic, producing the most intense Atlantic hurricane season of the historical record. By contrast, they note the summer and fall of 2006 were "characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans," and "this explains the weak tropical storm activity [of that year]."

Clearly, the temperature/hurricane connection is nowhere near as "one-dimensional" as Al Gore and others make it out to be. Warming alone does *not* ensure hurricanes will get stronger. Instead, as Latif *et al.* describe it, "the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region." They note "changes in the meridional overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered" and "changes in ENSO statistics in the tropical Pacific may become important."

Scileppi and Donnelly (2007) note "when a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats," and long-term records of hurricane activity are thus formed "as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers." Based on this knowledge, they refined and lengthened the hurricane record of the New York City area by calibrating the sedimentary record of surrounding backbarrier environments to documented hurricanes—including those of 1893, 1821, 1788, and 1693—and extracting several thousand additional years of hurricane history from the sedimentary archive.

The two researchers determined "alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales." They point out "several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550–1850 AD) when sea surface temperatures were generally colder than present," and "no major hurricanes have impacted this area since 1893," when Earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

Noting Emanuel (2005) and Webster *et al.* (2005) had produced analyses suggesting "cooler climate conditions in the past may have resulted in fewer strong hurricanes," whereas their own findings suggest just the opposite, Scileppe and Donnelly conclude "other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower sea surface temperatures" prior to the development of the Current Warm Period.

Briggs (2008) developed Bayesian statistical models for the number of tropical cyclones, the rate at which these cyclones became hurricanes, and the rate at which the hurricanes became Category 4+ storms in the North Atlantic, based on data from 1966 to 2006. He concluded there is "no evidence that the distributional mean of individual storm intensity, measured by storm days, track length, or individual storm power dissipation index, has changed (increased or decreased) through time."

Chylek and Lesins (2008) applied "simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity, and other features of interest." Noting "the last minimum in hurricane activity occurred around 1980," the two researchers compared the two 28-year-long periods on either side of this date and found "a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification." Hence, they conclude "if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured."

Vecchi *et al.* (2008) note "a key question in the study of near-term climate change is whether there is a causal connection between warming tropical sea surface temperatures (SSTs) and Atlantic hurricane activity." They explain in more detail the two schools of thought on this topic: one posits the intensity of Atlantic Basin hurricanes is directly related to the absolute SST of the basin's main development region, which would be expected to rise in response to global warming, and the other posits Atlantic hurricane intensity is directly related to the SST of the Atlantic basin's main development region relative to the SSTs of the other tropical ocean basins, which could either rise or fall to a modest degree in response to global warming—and possibly even cycle between the two modes.

Vecchi *et al.* proceeded to plot Atlantic hurricane power dissipation index (PDI) anomalies calculated from both the absolute SST values of the Atlantic Basin and the relative SST values derived from all tropical ocean basins as a function of time, extending them throughout most of the current century based on projections of the two parameters obtained from 24 climate models. They compared the results they obtained for the period 1946–2007 with the measured PDI anomalies. They found the relative SST "is as well correlated with Atlantic hurricane activity as the absolute SST." They also report the "relative SST does not experience a substantial trend in 21st-century projections," and therefore, "a future where relative SST controls Atlantic hurricane activity is a future similar to the recent past, with periods of higher and lower hurricane activity relative to present-day conditions due to natural climate variability, but with little long-term trend."

Vecchi *et al*. say their work "suggests that we are presently at an impasse," and "many years of data will be required to reject one hypothesis in favor of the other," as the projections derived from the absolute and relative SST parameters "do not diverge completely until the mid-2020s." If the absolute SST ultimately proves to be the proper forcing factor, projections of more-intense Atlantic hurricanes would have some validity. But if the relative SST proves to be the controlling factor, the researchers note, "an attribution of the recent increase in hurricane activity to human activities is not appropriate, because the recent changes in relative SST in the Atlantic are not yet distinct from natural climate variability."

Climate modelers are not quite ready to throw in the towel, as evidenced from a recent report from Bender *et al*. (2010). They "explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy by using an operational hurricane-prediction model that produces a realistic distribution of intense hurricane activity for present-day conditions," working with 18 models from the World Climate Research Program's Coupled Model Intercomparison Project 3 and employing the Intergovernmental Panel on Climate Change's A1B emissions scenario.

They found "an increase in the number of the most intense storms for the warmer climate compared with the control climate." Bender *et al*. predicted for "category 4 and 5 hurricanes with maximum winds greater than 60 m/s, the total number increased sharply from 24 to 46," and "hurricanes with winds greater than 65 m/s increased from 6 to 21." However, they also report there were reductions in the total number of hurricanes of all categories, which seems to contradict their own findings.

The researchers comment on the wide range of variability in the model predictions. They note, for example, an increase in hurricane-caused "damage potential" of +30% was projected for the 18-model ensemble, but a range of -50% to +70% was found for four models for which they did more detailed work. This extreme variability reduces confidence in their mean result.

Bender *et al*.'s findings clearly contradict the supposed link between the occurrence of strong hurricanes of the recent past with what many have claimed was unnatural and unprecedented CO_2-induced global warming. Quite to the contrary, and although the new model results suggest "a significant anthropogenic increase in the frequency of very intense Atlantic hurricanes may emerge from the background climate variability," the researchers say this development likely would not occur until "the latter half of the 21st century."

As is nearly always the case in climate modeling work, Kerr (2010) reports, in a commentary on Bender *et al*.'s study, that the researchers "are looking for yet more computer power and higher resolution to boost the realism of simulations." If those improvements are realized, and "if the models continue to converge as realism increases," Kerr writes, "the monster storms that seemed to be already upon us would be removed to decades hence."

But who really knows, when one is working with decidedly imperfect models of a complex planetary climate and weather system? As Kerr reports, even the researchers themselves "caution" their findings are still "far from the last word" on the subject.

Following up on an earlier paper (Chenoweth and Divine, 2008) in which they "presented a 318-year record of tropical cyclone activity in the Lesser Antilles and determined that there [was] no statistically significant change in the frequency of tropical cyclones (tropical storms and hurricanes) as well as tropical depressions over the entire length of the record," Chenoweth and Divine (2012) conducted a new analysis in which they examined the records employed in their earlier paper in more detail. They determined "the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian."

Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends. Chenoweth and Divine report their record of tropical cyclone activity "reveals no trends in LACE in the best-sampled regions for the past 320 years," and "even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or

LACE.” In addition, they note LACE along the 61.5°W meridian is “highly correlated” with Atlantic-Basin-wide ACE, suggesting their findings may extend beyond their region of study.

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7.8.1.3 El Niño Effect

How do Atlantic basin hurricanes respond to increases in temperature? In exploring this question within the context of the warming that occurs in going from cooler La Niña conditions to warmer El Niño conditions, Wilson (1999) analyzed data from the last half of the twentieth century, finding the probability of having three or more intense hurricanes was only 14% during a (relatively) warm El Niño year, but fully 53% during a (relatively) cool La Niña year. Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone the average ranged from 1.7 per La Niña season to 0.5 per El Niño season, a frequency-of-occurrence decline of fully 70% in going from cooler La Niña conditions to warmer El Niño conditions. Elsner *et al*. (2001), who also worked with data from the entire past century, also found "the probability of a U.S. hurricane increases" when there are below-normal sea surface temperatures in the equatorial Pacific.

Lyons (2004) conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three groupings: the 10 highest storm and hurricane landfall years, the nine lowest such years, and all other years. These groupings revealed, in Lyons' words, "La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years," and "El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years." In addition, "La Niña (El Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years."

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. They first determined 22 years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. They compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a 10-year study carried out on the other side of the Atlantic, Brichetti *et al.* (2000) determined, contrary to their own expectation, that survival rates for a Mediterranean water bird (Cory's Shearwater) were greater during warmer El Niño years than during cooler La Niña years.

Landsea *et al.* (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991–1994) that had exhibited the lowest such activity since the keeping of reliable records began. They determined the most important factor behind this transition was what they called the "dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions."

In a twentieth century changepoint analysis of time series of major North Atlantic and U.S. annual hurricane counts, which Elsner *et al.* (2004) say "quantitatively identifies temporal shifts in the mean value of the observations," the authors found "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

As for why North Atlantic hurricane activity is suppressed under warmer El Niño conditions, Donnelly and Woodruff (2007) opined it was "due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development." Such a conclusion is supported by the results of two analyses conducted by Klotzbach. Klotzbach (2011a) examined Caribbean tropical cyclone activity over the period 1900–2008, looking for impacts from the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). He found "the probability of one or more hurricanes and major hurricanes tracking through the Caribbean increases dramatically from 39% and 26% in the 10 warmest ENSO years to 92% and 63% in the 10 coldest ENSO years, respectively," in harmony with the similar findings of Tartaglione *et al.* (2003), who additionally demonstrated this cooling-induced response was likely due to "reductions in vertical wind shear and increases in low-level vorticity" in La Niña conditions. This connection also was demonstrated by Klotzbach, who determined "for the 10 warmest events since 1948, the average 200–850-mb zonal wind shear in the Caribbean was 7 m/s compared with only 3 m/s in the 10 coldest events since 1948."

The Colorado State University researcher also determined "the impacts of ENSO are reduced slightly when the AMO is positive," and he found "a negative AMO phase and El Niño combine to provide large-scale climate features that are especially hostile for tropical cyclones." He reports, for example, "29 hurricanes tracked into the Caribbean in the 10 strongest La Niña years in a positive AMO period compared with only two hurricanes tracking through the Caribbean in the 10 strongest El Niño years in a negative Atlantic multidecadal oscillation period."

Similar findings were reported in Klotzbach's second paper (2011b), which expanded his analysis beyond the Caribbean and throughout the Atlantic basin.

In addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes, there exists model-based evidence for the same conclusion. Vecchi and Soden (2007), for example, explored "21st Century projected changes in VS [vertical wind shear] over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions Scenario A1B (atmospheric CO_2 stabilization at 720 ppm by year 2100) for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4)," where VS was defined as "the magnitude of the vector difference between monthly-mean winds at 850 hPa and 200 hPa," and where "changes are computed between two 20-year periods: 2001–2020 and 2081–2100."

The analysis revealed the 18-model ensemble-mean projected change in VS over the twenty-first century is "a prominent increase in VS over the topical Atlantic and East Pacific (10°N–25°N)." Noting "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," they state the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century," and "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America."

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7.8.2 Indian Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Indian Ocean.

Hassim and Walsh (2008) analyzed tropical cyclone (TC) best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) for the presence of systematic intensity and duration trends over the cyclone season from 1969–1970 through 2004–2005. Their results indicated "the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones [increased] since 1980." A contemporaneous study of roughly the same region and time period by Harper *et al*. (2008) yielded a much different result.

Harper *et al*. analyzed several "potential influences on the accuracy of estimating TC intensity over time due to increasing technology, methodology, knowledge and skill" for TCs that occurred off the coast of northwestern Australia, primarily in a band between 5 and 25°S, over the period 1968–1969 to 2000–2001. The four Australian researchers show "a bias towards lower intensities likely exists in earlier (mainly pre-1980) TC central pressure deficit estimates of the order of at least 20% in 1970, reducing to around ten% by 1980 and to five% in 1985." They report "inferred temporal trends in the estimated intensity from the original data-sets are therefore significantly reduced in the objectively reviewed data-set." Thus they conclude "there is no prima facie evidence of a potential climate-change induced trend in TC intensity in northwestern Australia over the past 30 years."

Similar findings were reported two years later by Goebbert and Leslie (2010), who examined interannual TC variability of the northwest Australian (NWAUS) sub-basin of the southeastern Indian

Ocean (0–35°S, 105°–135°E) over the 39-year time period 1970–2008, using the Woodside Petroleum Ltd. reanalysis TC dataset described by Harper *et al.* (2008). The two researchers could find "no significant linear trends in either mean annual TC frequencies or TC days" and "no trend in the number of intense TCs for the NWAUS sub-basin." They note "none of the 13 NWAUS TC metrics exhibited statistically significant linear trends." They conclude, "known climate indices—such as Niño-3.4, Niño-4, SOI, NOI, PDO, NAO, and others—generally were found not to be significantly correlated to the variability of TC frequency or TC days in the NWAUS region."

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed "the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." Regarding the southeast Indian Ocean, for example, Hall determined "the overall number of depressions and tropical cyclones was below the long-term mean." Further east, he found broad-scale convection was near or slightly above normal, but "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which represented "a continuation of the trend of the previous few seasons." Hall's work, like that of Harper *et al.* (2008) and Goebbert and Leslie (2010), suggests a likely decline in both the intensity and frequency of Indian-Ocean tropical cyclones if the world warms in the future.

Singh *et al.* (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877–1998. The planet was recovering from the global chill of the Little Ice Age at this time, making it logical to assume their findings would be indicative of changes in hurricane characteristics that might be expected if Earth were to warm by that amount again, which is what the IPCC models project it will do.

On an annual basis, Singh *et al.* report there was a slight decrease in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one fewer hurricane per year at the end of the 122-year record in 1998 than at its start in 1877. In addition, based on data from the Bay of Bengal, they found tropical cyclone numbers dropped during the months of most severe cyclone formation (November and May) when the El Niño-Southern Oscillation was in a warm phase. In light of these observations, it would appear that if tropical cyclones of the North Indian Ocean were to change at all in response to global warming, their overall frequency and the frequency of the most intense such storms would likely decrease, just the opposite of what climate models typically suggest will occur.

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world and specifically the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report for the period 1891–1997 there was a significant decreasing trend (at the 99% confidence level) in the frequency of cyclones with the designation of "cyclonic storm" and above, and "the maximum decrease was in the last four decades," citing the work of Srivastava *et al.* (2000). In addition, they note Singh and Khan (1999) also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

Raghavan and Rajesh say "there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change." However, they continue, "studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones." Thus they confidently state "the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular media and even in some more serious publications, does not therefore have a sound scientific basis."

Kumar and Sankar (2010) say "an important concern about the consequences of the global warming scenario is its impact on the frequency, the intensity, and the duration of tropical cyclones," noting "theoretical and modeling studies indicate that tropical cyclone winds would increase with increasing ocean temperature." To see to what extent the implications of these theoretical model studies harmonize with what actually occurred throughout the North Indian Ocean over the period 1901–2007, Kumar and Sankar employed "various datasets, such as the NCEP/NCAR Reanalysis dataset, the ERSST and the tracks of storms and depressions over the north Indian Ocean for different seasons based on the period 1901–2007," comparing "changes that occurred during the period 1951–2007 and the previous period, 1901–1951." They also compared the sub-period 1951–1978 (epoch I) with the sub-period 1979–2007 (epoch II).

The two researchers determined "the frequency of storms and severe storms do not show a dramatic rise in spite of a substantial increase in the sea surface temperature in the Bay of Bengal from 1951–2007 compared to 1901–1951." Also, while noting "the Bay of Bengal has been warming throughout the year during epoch II compared to epoch I," they report "the number of both storms and severe storms, have decreased largely over the Bay of Bengal." Such findings, they write, "clearly indicate that warm SST's alone are not sufficient for the initiation of convective systems over the Arabian Sea and the Bay of Bengal," noting their results suggest a "decreasing trend in the frequency of storms over the Bay of Bengal, contrary to the popular belief that there will be an increase."

The authors note "in the current debate on global warming and the change in the number of intense cyclones, initial studies carried out have shown very different results for the northern Indian Ocean," where, as they describe it, "Webster *et al*. (2005) found that there had been a considerable increase in the number of categories 4 and 5 cyclones with a maximum sustained wind reaching at least 115 knots." They note, however, Landsea *et al*. (2006) subsequently demonstrated the databases employed by Webster *et al*. "were not sufficiently reliable," as "cyclones archived as being categories 2 or 3 had been re-analyzed and assigned as categories 4 or 5." They also note, "Kossin *et al*. (2007) did not note any trend towards an increase in the number of categories 4 and 5 cyclones in the northern Indian Ocean for their period of analysis, which covered from 1983 to 2005."

Hoarau *et al*. (2012) analyzed intense cyclone activity in the northern Indian Ocean from 1980 to 2009 on the basis of a homogenous reanalysis of satellite imagery. The three French researchers conclude "there has been no trend towards an increase in the number of categories 3–5 cyclones over the last 30 years," noting "the decade from 1990 to 1999 was by far the most active with 11 intense cyclones while 5 intense cyclones formed in each of the other two decades"; i.e., those that preceded and followed the 1990s. They state there has "not been a regular increase in the number of cyclone 'landfalls' over the last three decades (1980–2009)."

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7.8.3 Pacific Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Pacific Ocean.

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that originated in or entered the central North Pacific (0–70°N, 140–180°W) over the 32-year period 1966–1997. They found "tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise." This increase appears to have been due to a step-change that led to the creation of "fewer cyclones during the first half of the record (1966–81) and more during the second half of the record (1982–1997)." Accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity.

Although these findings may appear to support model-based projections that CO_2-induced global warming leads to more frequent and stronger hurricanes, Chu and Clark state the observed increase in tropical cyclone activity cannot be due to CO_2-induced global warming, because, in their words, "global warming is a gradual process" and "it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s."

A much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark and their relationship to mean global air temperature. The beginnings of such a history were presented by Liu *et al*. (2001), who waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975.

Calibrating the historical data against instrumental observations over the period 1884–1909, they found the trends of the two datasets were significantly correlated (r = 0.71), and this observation led them to conclude "the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls." They conducted a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that "suggests an external forcing mechanism, which remains to be identified." Also, and importantly, they found "the two periods of most frequent typhoon strikes in Guangdong (AD 1660–1680, 1850–1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age."

Hayne and Chappell (2001) studied a series of storm ridges at Curacoa Island, deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events affecting that area, with one of their stated reasons for doing so being to test the climate-model-based hypothesis that "global warming leads to an increase of cyclone frequency or intensity." They found "cyclone frequency was statistically constant over the last 5,000 years," and they could find "no indication that cyclones have changed in intensity."

Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S, by geologically dating and topographically surveying landform features left by historic hurricanes and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred during the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of their study. They also report the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The twentieth century was totally devoid of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

Noting "many researchers have suggested that the buildup of greenhouse gases (Watson *et al*., 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs)," Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data. They explain, "if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades."

Focusing on the last four decades of the twentieth century, they found a number of parameters related to SST and TC activity in the Western North Pacific (WNP) "have gone through large interannual as well as interdecadal variations," and "they also show a slight decreasing trend." In addition, they write, "no significant correlation was found between the typhoon activity parameters and local SST." They write, "in other words, an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models."

Chan and Liu suggest the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere. "In other words," they state, "the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999)," whereas "in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process." They conclude, "at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs."

Free *et al*. (2004) looked not for increases in actual hurricane intensity, but instead for increases in potential hurricane intensity, because "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." They used radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific and Atlantic Oceans and compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." Between 1975 and 1980, they further report, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This analysis indicated "the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, "the overall number of depressions and tropical cyclones was below the long-term mean." Further east he found broad-scale convection was near or slightly above normal, but "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which represented "a continuation of the trend of the previous few seasons." Hall writes, "in the eastern Australian region, the four-year period up to 2001–2002 was by far the quietest recorded in the past 41 years."

Noting Emanuel (2005) and Webster *et al*. (2005) had claimed "tropical cyclone intensity has increased markedly in recent decades" and "tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming," Ren *et al*. (2006) analyzed tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced torrential precipitation events. They report "significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years." They also state the downward trends were accompanied by "decreases in the numbers of TCs and typhoons that affected China during the period 1957–2004." In a conclusion that differs dramatically from the claims of Emanuel (2005) and Webster *et al*. (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al*. say their findings "strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP."

Wu *et al*. (2006) ran two independent checks on Webster *et al*.'s findings by performing analyses of best track data from the Regional Specialized Meteorological Centre (RSMC) Tokyo (Japan) and from the Hong Kong Observatory (HKO; Hong Kong, China). This work revealed, "in contrast to Webster *et al*.'s findings, there was no increase in western North Pacific category 4–5 typhoon activity," and "neither RSMC-Tokyo nor HKO best track data suggest an increase in western North Pacific tropical cyclone destructiveness as measured by the potential destructive index (PDI),” in contrast to the findings of Emanuel (2005).

Wu *et al.* state the RSMC-Tokyo data “show a decrease in the proportion of category 4–5 typhoons from 18% to 8% between the two periods 1977–1989 and 1990–2004,” noting “the result is the same if the analysis is extended to include 2005” and the trend is “statistically significant at the 5% level.” In addition, they report “HKO best track data show a decrease in the proportion of category 4–5 typhoons, from 32% to 16%, between 1975–1989 and 1990–2004,” noting this result too is “statistically significant at the 5% level” and it also “remains unchanged if the end year is extended to 2005.”

Nott *et al.* (2007) developed a 777-year-long annually resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. They found “the period between AD 1600 to 1800”—when the Little Ice Age held sway throughout the world—“had many more intense or hazardous cyclones impacting the site than the post AD 1800 period,” when the planet gradually began to warm. The four researchers point out “the only way to determine the likely future behavior of tropical cyclones is to first understand their history from high resolution records of multi-century length or greater.”

Li *et al.* (2007) analyzed tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949–2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951–2003. They used their empirical findings to infer future tropical cyclone activity in the region based on climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed there were “more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present.” They further found “the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones.”

Based on simulations of future occurrences of these favorable and unfavorable conditions derived from “a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios,” they then determined “the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it.”

Chan (2007) searched for “possible physical causes responsible for the interannual variations of the activity of intense typhoons in the WNP [Western North Pacific] (here defined as the region 0–40°N, 120–180°E).” The City University of Hong Kong researcher reports “in years with a high frequency of occurrence of intense typhoons, both the dynamic (relative vorticity in both the lower and upper troposphere as well as the vertical wind shear) and thermodynamic (as represented by the moist static energy in the low to mid troposphere) conditions in the atmosphere, especially in the eastern part of the WNP, are favorable for the formation of TCs [tropical cyclones],” and “once formed, these TCs tend to have longer lifetimes over the ocean, and therefore have a high chance to become more intense.” In addition, he notes the factors responsible for increasing the number of strong TCs are “also significantly correlated with the Niño3.4 SST anomalies.” Consequently, Chan reports, “the frequency of occurrence of intense typhoons in this region is not likely determined by the average SST over the region,” which is what would be expected to increase in response to greenhouse gas-induced global warming. Chan’s primary finding—that “interannual variations of intense typhoons in the WNP are likely caused to a large extent by changes in the planetary-scale atmospheric circulation and thermodynamic structure associated with the El Niño phenomenon”—provides no support for the contentions of either Emanuel (2005) or Webster *et al.* (2005).

Nott (2007) notes, “in tropical Australia, palaeo-tropical cyclone records occur in the form of low-resolution millennial-scale sedimentary ridges and high-resolution centennial-scale stalagmite records of isotopically depleted tropical cyclone rainfall.” He recounts the findings of those records and discusses their relevance to risk assessment and their role in “decoupling human induced changes in cyclone behavior from natural variability.” He states the clear message of the several papers he reviews is “the historical/instrumental record substantially under-estimates the frequency of the most extreme tropical cyclone events," citing the findings of Chappell *et al.* (1983), Chivas *et al.* (1986), Hayne and Chappell (2001), Nott and Hayne (2001), and Nott *et al.* (2007). He notes "tropical cyclone activity in north-east Queensland has been in a phase of quiescence since before European settlement of the region" and "the period between AD 1600 and 1800 [during the Little Ice Age] had many more intense or hazardous cyclones impacting the site than the post AD 1800 period."

In addition, Nott notes the first 200 years of the tropical cyclone record—from AD 1200 to 1400, which represents the latter part of the Medieval Warm Period (MWP)—had the fewest intense cyclones. According to the criterion he used to define them, this period of significant global warmth had none, as did the latter decades of the twentieth century. He found the entire twentieth century had but one such intense cyclone, in 1911, whereas there were as many as seven intense tropical cyclones during the global chill that prevailed between AD 1600 and 1800.

Chan (2008) further investigated possible causes of the multidecadal variability in intense TC [category 4 and 5] occurrence in the WNP, choosing this basin because it generally has the largest number of TCs each year. Based on data for the period 1960–2005, he determined decadal variations in intense typhoon activity largely resulted from a combination of the behavior of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). This finding led him to suggest "the view that global warming would lead to more intense TCs owing to the enhancement of thermodynamic factors ignores the fact that for TCs to intensify significantly, the dynamic factors must 'cooperate,'" which he notes has not been demonstrated to occur basin-wide. Therefore, he continues, "the more likely conclusion is that the major low-frequency variations in the frequency of intense TC occurrence is probably a multi-decadal one in response to similar variations in the factors that govern the formation, intensification and movement of TCs," and "such variations largely result from modifications of the atmospheric and oceanographic conditions in response to ENSO and PDO." Consequently, "at least for the WNP," Chan notes, "it is not possible to conclude that the variations in intense typhoon activity are attributable to the effect of global warming."

Defining rapid intensification (RI) of a tropical cyclone as occurring when the maximum wind speed of a TC "reaches at least (a) 5 knots in the first 6 hours, (b) 10 knots in the first 12 hours, and (c) 30 knots in 24 hours," Wang and Zhou (2008) state "all category 4 and 5 hurricanes in the Atlantic basin and 90% of the equivalent-strength typhoons in the western North Pacific experience at least one RI process in their life cycles." Using best-track TC data obtained from the Joint Typhoon Warning Center for the 40-year period 1965–2004, Wang and Zhou determined the climatic conditions most critical for the development of RI in TCs of the Western North Pacific on annual, intra-seasonal, and interannual time scales. They found "over the past 40 years, the annual total of RI in the western North Pacific shows pronounced interdecadal variation but no significant trend," and they note this "implies that the super typhoons had likely no upward trend in the last 40 years." In addition, they found "when the mean latitude, where the tropical storms form, shifted southward (either seasonally or from year to year), the proportion of super typhoons or major hurricanes will increase," noting "this finding contrasts the current notion that higher sea surface temperature leads to more frequent occurrence of category 4 or 5 hurricanes."

Englehart *et al.* (2008) developed a "first cut" dataset pertaining to the area immediately adjacent to Mexico's Pacific coast. Although noting only 54% of the total number of Eastern Pacific storms reached TC status within this near-shore area over the period 1967–2005, they report "near-shore storm activity is fairly well correlated with total basin TC activity, a result which suggests that over the longer period (i.e., 1921-onward), changes in near-shore activity can provide some sense of the broader basin activity." Their study revealed the existence of significant decadal variability in annual eastern Pacific near-shore TC frequency of occurrence. In addition, they found "long-term TC frequency exhibits a significant ($p = 0.05$) negative trend," which, as best can be determined from their graph of the data, declines by about 23% over the 85-year period 1921–2005. This result was driven solely by an approximate 30% drop in TC frequency during the late (August–November) TC season, with essentially no long-term trend in the early (May–July) TC season.

Englehart *et al.* present a graph of the maximum wind speed associated with each TC, from which one can calculate an approximate 20% decline in this intensity-related parameter over the period of their study. Their work provides no support for the claim that global warming increases the frequency and intensity of TCs and/or hurricanes.

Hassim and Walsh (2008) analyzed TC best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) and off Queensland and the Gulf of Carpentaria (the eastern sector: 135–160°E, Pacific Ocean) for the presence of systematic intensity and duration trends over the cyclone season periods running from 1969–1970 through 2004–2005. The two Australian researchers report "substantial differences in trends are found between the two sub-regions, with the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones increasing since 1980 in the west but decreasing (in number) or exhibiting no trend (in intensity, severe category duration) in the east."

Lu *et al*. (2008) also studied Western North Pacific (WNP) TCs during this time period, noting the WNP "is an area where typhoon activity is the most frequent and strongest" and "China is one of the countries that seriously suffered from typhoons in this area." Using TC data "in the yearbooks of TC of the WNP from 1960 to 2005," they analyzed the interdecadal variation of WNP TCs and the large-scale circulation factors affecting them. This analysis revealed "the time period from 1960 to 2005 has two high frequency periods (HFPs) and two low frequency periods (LFPs)," with the overall trend being downward (see Figure 7.8.3.1).

One year later, noting "the variability of TC activity (including the frequency of occurrence and intensity) has become a great concern because it may be affected by global warming," Kubota and Chan (2009) created a unique dataset of TLP (tropical cyclone landfall numbers in the Philippines) based on historical observations of TC tracks during the period 1901–1940 obtained from monthly bulletins of the Philippine Weather Bureau and combined with TLP data obtained from the Joint Typhoon Warning Center for the period 1945–2005, which they used to investigate the TC-global warming hypothesis. The two Asian researchers found "the TLP has an apparent oscillation of about 32 years before 1939 and an oscillation of about 10–22 years after 1945," but "no long-term trend is found." In addition, they determined "natural variability related to ENSO and PDO phases appears to prevail in the interdecadal variability of TLP," and their results show all variability was merely oscillatory activity around a mean trend of zero slope (see Figure 7.8.3.2).

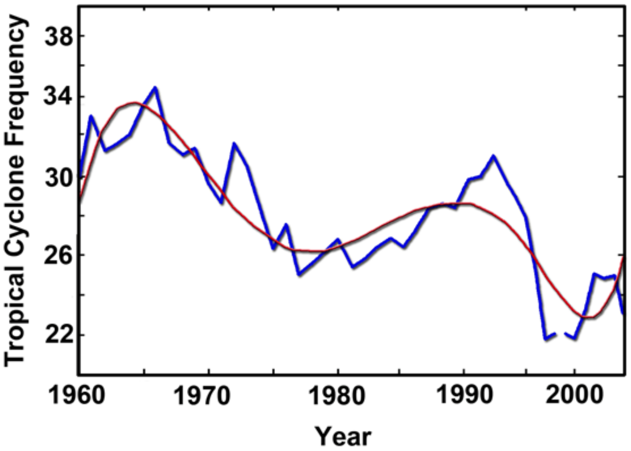

Figure 7.8.3.1. Tropical cyclone frequency vs. year. Blue line represents five-year running means, while the red line is a fifth-order polynomial that has been fitted to the data points. Adapted from Lu, Q-z., Hu, B-h., Wang, J. and Zhang, Y. 2008. Impact of large-scale circulation on the interdecadal variations of the western North Pacific tropical cyclone. *Journal of Tropical Meteorology* **14**: 1006–8775(2008) 01-0081-04.

Ma and Chen (2009) used NCEP/NCAR reanalysis data to determine the SST distribution over this region and to evaluate its temporal variability, utilizing TC frequency data obtained from the Joint Typhoon Warning Center, the *Tropical Cyclone Year Book* of the China Meteorological Administration, and the Tokyo-Typhoon Center of the Japanese Meteorological Agency to characterize TC frequency over the period 1949–2007. This work revealed, "SSTs over the WNP have been gradually increasing during the past 60 years ... with a maximum increment of 1°C around the central equatorial Pacific for the last 10 years." They also state "the warm pool, which is defined to be enclosed by a critical temperature of 28°C, has expanded eastward and northward in recent years," noting further "there has been remarkable warming in the last decade, more than 0.8°C in some local areas." Nevertheless, and in spite of this "remarkable warming," the two researchers determined "the frequency of TC against the background of global warming has decreased with time."

Chan and Xu (2009) used TC data obtained from the Joint Typhoon Warning Center for the period 1945–2004 and the *Annual Tropical Cyclone Data Book* (edited by the Shanghai Typhoon Institute) for the period 1951–2000 to conduct a comprehensive study of variations in the annual number of landfalling TCs in three sub-regions of East Asia: South (south China, Vietnam, and the Philippines),

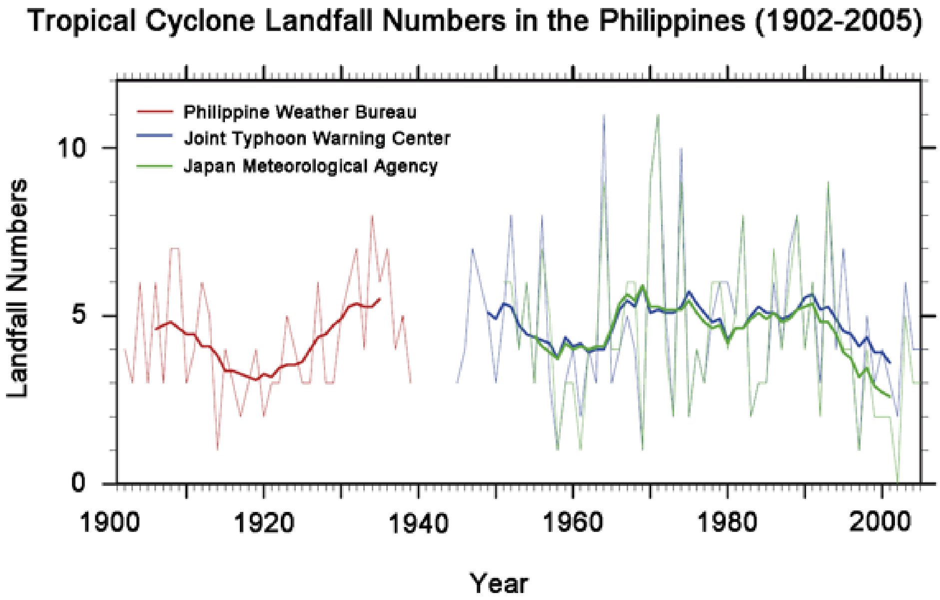

Figure 7.8.3.2. Tropical cyclone landfall numbers in the Philippines over the period 1902-2005. Adapted from Kubota, H. and Chan, J.C.L. 2009. Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. *Geophysical Research Letters* **36**: 10.1029/2009GL038108.

Middle (east China), and North (Korean Peninsula and Japan). They report "wavelet analyses of each time series show that the landfalling frequencies go through large inter-annual (2–8 years), inter-decadal (8–16 years) and even multi-decadal (16–32 years) variations, with the inter-annual being the most dominant, and the multi-decadal explaining most of the rest of the variance." In what they call "an important finding," they state "none of the time series shows a significant linear temporal trend, which suggests that global warming has not led to more landfalls in any of the regions in Asia."

Song *et al*. (2010) point out, "in recent years, there has been increasing interest in whether global warming is enhancing tropical cyclone (TC) activity," as has been claimed by Emanuel (2005) and Webster *et al*. (2005). They note Wu *et al*. (2006) and Yeung (2006) found "no increase in category 4–5 typhoon activity in the western North Pacific basin," "in contrast to Webster *et al*. (2005)."

In addition, Song *et al*. report "neither RSMC nor HKO best track data suggest an increase in TC destructiveness." They further state "other studies also examined the differences in TC data sets from the Joint Typhoon Warning Center (JTWC) of the U.S. Naval Pacific Meteorology Oceanography Center in Hawaii, the RSMC, and the Shanghai Typhoon Institute (STI) of [the] China Meteorological Administration in Shanghai (Lei, 2001; Kamahori *et al*., 2006; Ott, 2006; Yu *et al*., 2007)," and "so far, the reported trends in TC activity in the WNP basin have been detected mainly in the JTWC best track data set," which was the one employed by Emanuel (2005) and Webster *et al*. (2005) in drawing their anomalous conclusions.

To help resolve the anomalies exhibited by the JTWC typhoon database, Song *et al*. analyzed differences in track, intensity, frequency, and the associated long-term trends of those TCs that were simultaneously recorded and included within the best track data sets of the JTWC, the RSMC, and the STI from 1945 to 2007. They determined "though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2–3 as category 4–5, leading to an upward trend in the annual frequency of category 4–5 TCs and the annual accumulated power dissipation index, as reported by Webster *et al*. (2005) and Emanuel (2005)." They state "this trend and potential destructiveness over the period 1977–2007 are found only with the JTWC data set," while noting downward trends "are apparent in the RSMC and STI data sets."

Fengjin and Ziniu (2010) used data obtained from the China Meteorological Administration on the time and site of TC generation and landfall, TC tracks, and the intensity and duration of TCs in the WNP and China for the period 1951–2008 to analyze the characteristics of TCs making landfall in China over that period. This work revealed "a decreasing trend in the generation of TCs in the WNP since the 1980s," and they note the number of TCs making landfall during this period "has remained constant or shown only a slight decreasing trend." They also report "the number of casualties caused by TCs in China appears to show a slight decreasing trend.

Terry and Gienko (2010) analyzed various cyclone characteristics based on four decades of cyclone season data (1969–1970 to 2007–2008) in the regional cyclone archive of the tropical South Pacific (160°E–120°W, 0°–25°S) maintained by the Regional Specialized Meteorological Centre (RSMC) located at Nadi in the Fiji Islands. They state "no linear trends were revealed in cyclogenesis origins, cyclone duration, track length or track azimuth over the four decades of records," but "anomalous activity for one or more cyclone parameters occurred in 1976, 1981, 1983, 1991, 1998, 2001–2002 and 2003," leading them to conclude "there is as yet no evidence for climate-change forcing of these storm characteristics over recent historical times."

Sun *et al*. (2011) analyzed data pertaining to TCs over the northwestern Pacific and the South China Sea, obtained from China's Shanghai Typhoon Institute and the National Climate Center of the China Meteorological Administration, pertaining to the period 1951 to 2005. They determined the frequency of all TCs impacting China "tended to decrease from 1951 to 2005, with the lowest frequency [occurring] in the past ten years" (see Figure 7.8.3.3). In addition, they state the average yearly number of super typhoons was "three in the 1950s and 1960s" but "less than one in the past ten years." They write "the decrease in the frequency of super typhoons, at a rate of 0.4 every ten years, is particularly significant (surpassing the significance test at the 0.01 level)" (see Figure 7.8.3.4), adding "there is a decreasing trend with the extreme intensity of these TCs during the period of influence in the past 55 years."

Callaghan and Power (2011) developed and used "a new data base of severe land-falling TCs for eastern Australia derived from numerous historical sources, that has taken over a decade to develop." This database, they continue, includes "peer-reviewed publications; Bureau of Meteorology publications, including comprehensive case histories for a large number of TCs – including all TCs since the mid-1950s, *Monthly Climatological Bulletins* and *Monthly Weather Reviews*, unpublished TC season reports, bounded operational analysis charts back to the 1890s stored in the National Archives, unpublished internal Bureau documents; publications by state and local governments; archives of several Queensland newspapers; newspaper clippings held by the Bureau of Meteorology; books describing land-falling TCs; information held by the Cairns and Townsville Historical Societies; a report to the QLD parliament (1918); and extensive unpublished information from the public including numerous damage photographs," as well as "reports on storm surge, wave action and shipwreck data from an extensive Australian shipwreck data base."

The two researchers with Australia's Bureau of Meteorology note their new database allows them "to document changes over much longer periods than has been done previously for the Southern Hemisphere." Among the host of results they describe, two of them stand out with respect to their significance to the global warming debate. First, they report "the sign and magnitude of trends calculated over 30 years periods vary substantially," noting "caution needs to be taken in making inferences based on *e.g.* satellite era data only." Second, they report "the linear trend in the number of severe TCs making land-fall over eastern Australia declined from about 0.45 TC/year in the early 1870s to about 0.17 TC/year in recent times—a 62% decline." They note "this decline can be partially explained by a weakening of the Walker Circulation, and a natural shift towards a more El Niño-dominated era." Thus they conclude the abstract of their paper by saying, "the extent to which global warming might also be partially responsible for the decline in land-falls—if it is at all—is unknown," suggesting global warming might be doing just the opposite of what climate models typically suggest it should do.

Noting the Intergovernmental Panel on Climate Change (IPCC, 2001, 2007) has twice suggested "precipitation and extreme winds associated with tropical cyclones may have become more intense," Ying *et al.* (2011) remind us this claim is "mainly based on numerical models." Working with tropical cyclone best track and related observational severe wind and precipitation datasets created by the Shanghai Typhoon Institute of the China Meteorological Administration, the four researchers identified trends in observed TC characteristics over the period 1955 to 2006 for the whole of China and four sub-regions: South China (SC), comprising Guangdong, Guangxi, and Hainan Provinces; East

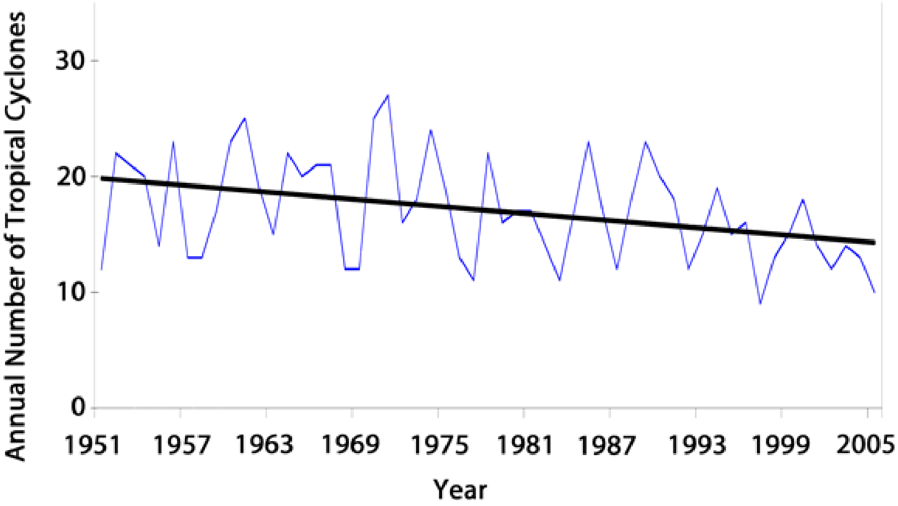

Figure 7.8.3.3. Number of typhoons affecting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* **17**: 181-186.

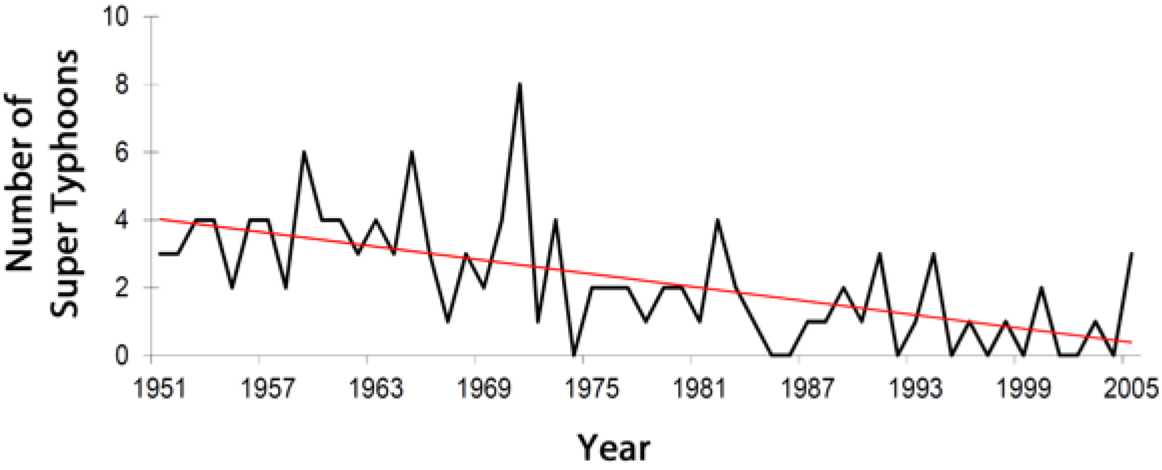

Figure 7.8.3.4. Frequency of super typhoons impacting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* **17**: 181-186.

China (EC), comprising Fujian, Hiangxi, Zhejiang, Anhui, Jiangsu, and Shandong Provinces plus Shangahi; Northeast China (NEC), comprising Liaoning, Jilin, and Heilongjiang Provinces; and China's inland area (CI) including all remaining provinces.

They found over the past half-century there have been no changes in the frequency of TC occurrence, except within NEC, where they determined "years with a high frequency of TC influence have significantly become less common." They also note, "during the past 50 years, there have been no significant trends in the days of TC influence on China" and "the seasonal rhythm of the TC influence on China also has not changed." They found "the maximum sustained winds of TCs affecting the whole of China and all sub-regions have decreasing trends" and "the trends of extreme storm precipitation and 1-hour precipitation were all insignificant." Thus, for the whole of China and essentially all of its component parts, major measures of TC impact have remained constant or slightly decreased, a much different consequence from what the IPCC has been predicting for the world over the past decade or more.

Xiao *et al*. (2011) "developed a Tropical Cyclone Potential Impact Index (TCPI) based on the air mass trajectories, disaster information, intensity, duration and frequency of tropical cyclones," using observational data obtained from the China Meteorological Administration's *Yearbook of Tropical (Typhoon) Cyclones in China* for the years 1951–2009 plus the *Annual Climate Impact Assessment* and *Yearbook of Meteorological Disasters* in China, also compiled by the China Meteorological Administration, but for the years 2005–2009. The five researchers report "China's TCPI appears to be a weak decreasing trend over the period [1949–2009], which is not significant overall, but significant in some periods."

Ren *et al*. (2011) write "the homogeneity of historical observations is important in the study of tropical cyclones and climate change," with "a large hurdle for climate change detection" being "the quality of TC historical databases," which they say "were populated over time without a focus on maintaining data homogeneity," "a key requirement for databases that are used to assess possible climate-related trends." In an effort to overcome this hurdle, which they describe as "a 'bottleneck' in tropical cyclone and climate change studies," Ren *et al*. analyze three historical datasets for Western North Pacific TCs—those of the Joint Typhoon Warning Center (JTWC), the Japan Meteorological Agency (JMA), and the China Meteorological Administration (CMA)—focusing primarily on TC intensity and covering the 55-year period 1951–2005.

The five researchers conclude "it is still difficult to judge which one [of the three datasets] is best." They indicate frequencies of the common TCs in all three datasets "show no obvious increasing or decreasing trend over the past 50 years." Instead, they find a weak interdecadal variation with "more TCs from the mid-1960s to the mid-1970s and in the early 1990s." By contrast, they state the intensities of the common TCs "differed largely from one dataset to another, leading to quite opposite conclusions for TCs of category 4 and 5." For example, they note "for the period after 1970, the JTWC dataset shows an increasing trend that complies with those of Webster *et al*. (2005) and Emanuel (2005)," but "for a longer time scale, the result may be well consistent with that of Chan (2006)," which suggests "the so-called 'trend' is a fragment of the longer inter-decadal variation."

Zhang *et al*. (2011) analyzed both the frequency and intensity of TCs that made landfall on the Pacific coast of South China's Guangdong Province between 1965 and 2007. Employing data extracted from the database collected by the Shanghai Typhoon Institute of the China Meteorological Administration, together with pertinent sea surface temperature (SST) data for the Pacific Ocean obtained from the UK Met Office's Hadley Centre, the four Chinese researchers studied the changing properties of the frequency and intensity of the TCs making landfall at the Guangdong Province (TMLGP) as functions of time and temperature.

They found the frequency of TMLGP after 1996 had "a nearly opposite trend compared to the period preceding 1996" and determined "the frequency of TMLGP for the period 1965–2007 as a whole is in an insignificant relation with SST in these two periods." They also found various SST measures "only have a weak influence on TMLGP intensities." They note, "despite the long-term warming trend in SST in the Western North Pacific, no long-term trend is observed in either the frequency or intensities of TMLGP."

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7.8.4 Global

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the entire globe.

Climate models have long suggested the intensity and frequency of hurricanes or tropical cyclones (TCs) may be significantly increased in response to global warming, as noted by Free *et al*. (2004), who have written "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming," citing in support of this statement the studies of Emanuel (1987), Henderson-Sellers *et al*. (1998), and Knutson *et al*. (1998). Before accepting this climate-model-based projection, it is important to consider what drives tropical cyclone activity in the real world.

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) conclude "the effect of global warming on the number of tropical cyclones is presently unknown," and "there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe." They report there is "little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers."

In a second early analysis of the topic, Henderson-Sellers *et al*. (1998) determined "there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses," "global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill," and "the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy."

Walsh (2004) acknowledged "there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming." Nevertheless, Walsh suggested "there is likely to be some increase in maximum tropical cyclone intensities in a warmer world," "it is probable that this would be accompanied by increases in mean tropical cyclone intensities," and "these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%." He put the date of possible detection of these increases "sometime after 2050," little knowing two such claims would be made the very next year.

The historic contentions came from Emanuel (2005), who claimed to have found a hurricane power dissipation index had increased by approximately 50% for the Atlantic basin and the Northwest Pacific basin since the mid-1970s, and from Webster *et al*. (2005), who contended the number of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975–1989) and a more recent (1990–2004) 15-year period. In a challenge to both these claims, Klotzbach (2006) wrote "many questions have been raised regarding the data quality in the earlier part of their analysis periods," and he performed a new analysis based on a "near-homogeneous" global dataset for the period 1986–2005.

Klotzbach first tabulated global tropical cyclone (TC) activity using best track data, which he described as "the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers," for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian, and South Pacific). He then determined trends of worldwide TC frequency and intensity over the period 1986–2005, during which time global SSTs are purported to have risen by about 0.2–0.4°C. Klotzbach found "a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin," but also "a considerable decreasing trend for the Northeast Pacific." Combining these observations with the fact that "all other basins showed small trends," he concluded there had been "no significant change in global net tropical cyclone activity" over the past two decades.

With respect to Category 4 and 5 hurricanes, Klotzbach found there had been a "small increase" in their numbers from the first half of the study period (1986–1995) to the last half (1996–2005), but he noted "most of this increase is likely due to improved observational technology." Klotzbach declared his findings were "contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al.* (2005)," in that the global TC data did "not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years."

Landsea *et al.* (2006) asked whether "the global tropical cyclone databases [are] sufficiently reliable to ascertain long-term trends in tropical cyclone intensity, particularly in the frequency of extreme tropical cyclones (categories 4 and 5 on the Saffir-Simpson Hurricane Scale)." They analyzed the history of a number of operational changes at various tropical cyclone warning centers they theorized might have led to "more frequent identification of extreme tropical cyclones," as well as an unreal "shift to stronger maximum sustained surface wind," investigating in particular in this regard the Dorvak Technique for estimating tropical cyclone intensity.

The four researchers found "trend analyses for extreme tropical cyclones are unreliable because of operational changes that have artificially resulted in more intense tropical cyclones being recorded [with the passing of time], casting severe doubts on any such trend linkages to global warming." In addition, they note "data from the only two basins that have had regular aircraft reconnaissance—the Atlantic and Northwest Pacific—show that no significant trends exist in tropical cyclone activity when records back to at least 1960 are examined (Landsea, 2005; Chan, 2006)," while additionally noting "Klotzbach (2006) has shown that extreme tropical cyclones and overall tropical cyclone activity have globally been flat from 1986 until 2005, despite a sea surface temperature warming of 0.25°C."

Kossin *et al.* (2007) note "the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous," adding this "known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates." As an important first step in resolving this problem, Kossin *et al.* "constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates." They analyzed the resultant homogenized data for temporal trends over the period 1984–2004 for all major ocean basins and the global ocean as a whole.

The five scientists report, "using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic." Therefore, noting "the Atlantic basin accounts for less than 15% of global hurricane activity," they conclude "this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity." They concluded, "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future."

Vecchi and Soden (2007) used climate models and real-world observations "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They conclude "changes in local sea surface temperature are inadequate for characterizing even the sign of changes in potential intensity."

Reporting on the International Summit on Hurricanes and Climate Change held in May 2007 on the Greek island of Crete, where 77 academics and stakeholders from 18 countries participated in a free-ranging discussion of hurricanes and climate change, Elsner (2008) writes, "the question of whether we can ascribe a change in tropical cyclone intensity to anthropogenic climate change is still open." On the question of a warming-induced increase in hurricane frequency, he states the science was even more unsettled. Although "most models," in his words, indicate "an overall decrease in the number of storms," he notes not even all models agree on the change in individual basin tropical cyclone numbers, "with some models showing an increase in the Atlantic and others a decrease."

Further confusion was raised by Nolan and Rappin (2008), who extended the methodology of Nolan *et al*. (2007) to include a prescribed wind as a function of height that remains approximately constant during the genesis of tropical cyclones in environments of radiative-convective equilibrium partially defined by sea surface temperature (SST). They employed the modified methodology to explore what happens when SSTs rise. This approach revealed "increasing sea surface temperature does not allow TC genesis to overcome greater shear." In fact, they note "the opposite trend is found," and "the new and surprising result of this study is that the effect of shear in suppressing TC genesis actually increases as the SST of the radiative-convective equilibrium environment is increased."

This model-based finding was analogous to the observation-based result of Vecchi and Knutson (2008), who found as the SST of the main development region of North Atlantic TCs had increased over the past 125 years, certain aspects of climate changed in ways that may have made the North Atlantic "more favorable to cyclogenesis, while at the same time making the overall environment less favorable to TC maintenance." It is interesting that Nolan and Rappin conclude their paper with the intriguing question, "Do these results explain recent general circulation modeling studies predicting fewer tropical cyclones in a global warming world (e.g., Bengtsson *et al*. 2007)?"

Fan and Liu (2008) present a brief review and synthesis of the major research advances and findings of paleotempestology, which they describe as "a young science" that "studies past typhoon activity spanning several centuries to millennia before the instrumental era through the use of geological proxies and historical documentary records." They found "there does not exist a simple linear relationship between typhoon frequency and Holocene climate (temperature) change," especially of the type suggested by climate models. They report "on the contrary, typhoon frequency seemed to have increased at least regionally during the coldest phases of the Little Ice Age." They also note "more typhoons and hurricanes make landfalls in China, Central and North America during [cooler] La Niña years than [warmer] El Niño years." Consequently, and following their own advice about the need "to extend the time span of typhoon activity records" to help resolve the debate over the nature of climate change effects on this important weather phenomenon, Fan and Liu demonstrated the models likely have even the sign of the temperature effect on typhoon activity wrong, as global warming seems to reduce tropical cyclone activity over both the long term and the short term.

Chan (2009) studied five ocean basins—the Atlantic (1960–2007), Western North Pacific (1960–2007), Eastern North Pacific (1960–2007), South Indian Ocean (1981–2007), and South Pacific (1981–2007)—examining the relationship between the seasonally averaged maximum potential intensity (MPI, an index of thermodynamic forcing) over each basin and the frequency of occurrence of intense TCs within that basin. This work revealed "only in the Atlantic does the MPI have a statistically significant relationship with the number of intense TCs, explaining about 40% of the [observed] variance," whereas "in other ocean basins, there is either no correlation or the correlation is not significant." Even in the Atlantic, where a significant correlation exists between thermodynamic or temperature-related factors and the frequency of intense TCs, it is not clear whether global warming will produce a net increase in TC frequency, because model projections also suggest the increase in vertical wind shear associated with an increase in sea surface temperature tends to work against intense TC development. Therefore, Chan concludes, "it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario."

Wang and Lee (2009) note in the Western Hemisphere, tropical cyclones "can form and develop in both the tropical North Atlantic (NA) and eastern North Pacific (ENP) Oceans, which are separated by the narrow landmass of Central America," and "in comparison with TCs in the NA, TCs in the ENP have received less attention, although TC activity is generally greater in the ENP than in the NA (e.g., Maloney and Hartmann, 2000; Romero-Vadillo *et al*., 2007)." In exploring how the TC activities of the NA and ENP ocean basins might be related to each other over the periods 1949–2007 and 1979–2007, they employed several datasets to calculate the index of accumulated cyclone energy (ACE), which accounts for the number, strength, and duration of all TCs in a given season. They discovered "TC activity in the NA varies out-of-phase with that in the ENP on both interannual and multidecadal timescales," so "when TC activity in the NA increases (decreases), TC activity in the ENP decreases (increases)." In addition, they found "the out-of-phase relationship seems to [have] become stronger in the recent decades." The interannual and multidecadal correlations between the NA and ENP ACE indices were -0.70 and -0.43, respectively, for the period 1949–2007, but -0.79 and -0.59, respectively, for the period 1979–2007. In terms of the combined TC activity over the NA and ENP ocean basins as a whole, there is little variability on either interannual or multidecadal timescales. The real-world empirical data thus suggest the variability that does exist over the two basins has grown slightly weaker as Earth has warmed over the past six decades, running counter to claims that Earth's hurricanes or tropical cyclones should become more numerous, stronger, and longer-lasting as temperatures rise.

Wang *et al*. (2010) examined cross-basin spatial-temporal variations of TC storm days for the Western North Pacific (WNP), Eastern North Pacific (ENP), North Atlantic (NAT), North Indian Ocean (NIO), and Southern Hemisphere Ocean (SHO) over the period 1965–2008, for which period satellite data were obtained from the U.S. Navy's Joint Typhoon Warning Center for the WNP, NIO, and SHO, and from NASA's U.S. National Hurricane Center for the NAT and ENP. They report "over the period of 1965–2008, the global TC activity, as measured by storm days, shows a large amplitude fluctuation regulated by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, but has no trend, suggesting that the rising temperature so far has not yet [had] an impact on the global total number of storm days." This further implies "the spatial variation of SST, rather than the global mean temperature, may be more relevant to understanding the change of the global storm days."

Maue (2011) obtained global TC life cycle data from the IBTrACS database of Knapp *et al*. (2010), which contains six-hourly best-track positions and intensity estimates for the period 1970–2010, from which he calculated the accumulated cyclone energy (ACE) metric (Bell *et al*., 2000), which is analogous to the power dissipation index (PDI) used by Emanuel (2005) in his attempt to link hurricanes with global warming. Maue found "in the pentad since 2006, Northern Hemisphere and global tropical cyclone ACE has decreased dramatically to the lowest levels since the late 1970s." He also found "the global frequency of tropical cyclones has reached a historical low." He noted "a total of 69 TCs were counted during calendar year 2010, the fewest observed in the past 40 years with reliable frequency data." Over the four-decade period, "12-month running-sums of the number of global TCs of at least tropical storm force has averaged 87," and "the minimum number of 64 TCs was recently tallied through May 2011." Maue noted "there is no significant linear trend in the frequency of global TCs," in agreement with the analysis of Wang *et al*. (2010). "[T]his current period of record inactivity," as Maue describes it, suggests the long-held contention that global warming increases the frequency and intensity of tropical storms is simply not true.

Noting "Quaternary data have not figured prominently in recent debates concerning TC natural variability versus potential anthropogenic global warming-induced changes, nor have the Quaternary data been used to any substantial degree in numerical model projections concerning the future behavior of TCs," Nott (2011) provided a brief review of the subject, wring there are "at least 15 different methods for reconstructing long-term records of TCs."

The Australian researcher reports "recent analyses of corrected historical TC records suggest that there are no definitive trends towards an increase in the frequency of high-intensity TCs for the Atlantic Ocean region (Knutson *et al*., 2010), the northwest Pacific (Chan, 2006; Kossin *et al*., 2007) and the Australian region, South Pacific and south Indian oceans (Kuleshov *et al*., 2010)." He points out, "over multi-century to millennial timescales, substantial change has occurred in virtually all TC-generating regions of the globe," with "alternating periods of lesser and greater activity." He notes "the longer, coarser-resolution records display periods from multi-century to over a millennium in length, whereas the higher-resolution records register multi-decadal to centennial-length periodicities."

In some of these cases, Nott states, "different climate states, such as periods dominated by El Niños and La Niñas, appear to be responsible for the TC variability," whereas in other cases the responsible factor seems to be shifts in the position of the jet stream, solar variability, or some unknown cause. Nott notes "there is still considerably more data needed before causes of the long-term variability of TCs can be comprehensively identified" and "a better understanding of this long-term variability will be critical to understanding the likely future behavior of TCs globally and especially so when attempting to detect and attribute those future changes."

In a study designed to explore "the question of whether and to what extent global warming may be changing tropical cyclone activity," Grossmann and Morgan (2011) reviewed the scientific literature related to the possible effects on TC frequency and intensity of climate-model projected consequences of continued atmospheric greenhouse gas enrichment. They found "while Atlantic TCs have recently become more intense, evidence for changes in other basins is not persuasive, and changes in the Atlantic cannot be clearly attributed to either natural variability or climate change." They state "the presence of a possible climate change signal in TC activity is difficult to detect because inter-annual variability necessitates analysis over longer time periods than available data allow," and because "projections of future TC activity are hindered by computational limitations and uncertainties about changes in regional climate, large-scale patterns, and TC response."

While noting "scientific uncertainty about whether and how climate change will affect TCs in the future may not be resolved for decades," Grossmann and Morgan go on to suggest even if climate change "does not result in any significant increase in the intensity or frequency of future tropical cyclones" nor "lead to significant sea-level rise," human vulnerability in areas prone to land-falling hurricanes "will likely continue to increase significantly due to the continuing growth of populations and capital stock in high risk areas," citing Pielke *et al.* (2008). They conclude it would be wise "to induce greater protective action," and "there is a need to act now to reduce the existing high vulnerability to these storms," which will continue to constitute a real and present danger to people and infrastructure in coastal areas regardless of whether the frequency and degree of that danger increases or decreases.

Although many studies have explored the impacts of changes in sea surface temperature on various properties of tropical cyclones, the reverse phenomenon—the impacts of TCs on SSTs—has been less discussed. It has been known for decades, however, as reported by Dare and McBride (2011), that strong winds associated with TCs tend to reduce SSTs beneath such storms, as described by Fisher (1958), Leipper (1967), Brand (1971), Price (1981), Bender *et al.* (1993), Hart *et al.* (2007), Price *et al.* (2008), Jansen *et al.* (2010), and Hart (2011). This cold surface wake, as they describe it, "may extend for hundreds of kilometers adjacent to the storm track (Nelson, 1996; Emanuel, 2001)," and it can spread to larger scales over time, as reported by Sobel and Camargo (2005). As for the magnitude of the SST reduction within the TC wake, Dare and McBride write it can "range from less than 1°C (Cione *et al.*, 2000), up to 3° (Shay *et al.*, 1991), 4° (Price *et al.*, 2008), 5° (Price, 1981), 6° (Berg, 2002), 7° (Walker *et al.*, 2005), and 9°C (Lin *et al.*, 2003)."

Using the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al.*, 2009) to provide the latitudes and longitudes at six-hour intervals for all TCs that occurred worldwide between September 1, 1981 and December, 31 2008, together with a corresponding set of SST data provided by NOAA's National Climatic Data Center at every 0.25° of latitude and longitude (Reynolds *et al.*, 2007), Dare and McBride calculated the mean magnitude of the SST reductions and the average amount of time required for the reduced SSTs to return to pre-storm values. This effort revealed the time of maximum SST cooling occurred one day after cyclone passage, when the SST depression averaged 0.9°C. Thereafter, they report 44% of the SST depressions returned to normal within five days, while 88% of them recovered within 30 days. And although there were differences among individual cyclone basins, they say the individual basin results were in broad agreement with the global mean results. Finally, they report "cyclones occurring in the first half of the cyclone season disrupt the seasonal warming trend, which is not resumed until 20–30 days after cyclone passage," while "cyclone occurrences in the latter half of the season bring about a 0.5°C temperature drop from which the ocean does not recover due to the seasonal cooling cycle." Each TC occurring somewhere in the world leaves behind it a significantly altered SST environment that would be expected to have an effect 20 to 30 days later on other TCs that might pass through the same location.

Manucharyan *et al.* (2011) analyzed the effects of TCs on other TCs using several representative cases of time-dependent mixing that yielded the same annual mean values of vertical diffusivity, conforming with the studies of Jansen and Ferrari (2009) and Fedorov *et al*. (2010), wherein spatially uniform (but varying in time) mixing is imposed on zonal bands in the upper ocean. This work revealed "a weak surface cooling at the location of the mixing (~0.3°C), a strong warming of the equatorial cold tongue (~2°C), and a moderate warming in middle to high latitudes (0.5°C–1°C)," together with "a deepening of the tropical thermocline with subsurface temperature anomalies extending to 500 m [depth]." They state "additional mixing leads to an enhanced oceanic heat transport from the regions of increased mixing toward high latitudes and the equatorial region." But "ultimately," they continue, "simulations with TC-resolving climate models will be necessary to fully understand the role of tropical cyclones in climate," for they note "the current generation of GCMs [is] only slowly approaching this limit and [is] still unable to reproduce many characteristics of the observed hurricanes, especially of the strongest storms critical for the ocean mixing (e.g., Gualdi *et al*., 2008; Scoccimarro *et al*., 2011)."

Nott and Forsyth (2012) write, "understanding the long-term natural variability of tropical cyclones (TCs) is important for forecasting their future behavior and for the detection and attribution of changes in their activity as a consequence of anthropogenically induced climate change." They point out, "critical to these endeavors is determining whether, over the long-term, TCs occur randomly or display identifiable patterns influenced by one or several factors."

The two researchers present "new sedimentary data from the southwest (SW) Pacific and southeast (SE) Indian Ocean regions which allow us to make comparisons with existing sediment records from the Atlantic Ocean (Donnelly and Woodruff, 2007; Mann *et al*., 2009), northwest (NW) Pacific (Woodruff *et al*., 2009), Gulf of Mexico (Liu and Fearn, 1993, 2000; Lane *et al*., 2011) and the Gulf of Carpentaria, Australia (Rhodes *et al*., 1980)." They find "long-term global TC activity is not random." Instead, there is "a substantial degree of synchroneity in global intense TC behavior over the past 3,000 to 5,000 years." And they report "one of the most striking aspects of these records is they all display extended alternating periods (centuries to millennia) of relative quiescence and heightened intense TC activity irrespective of both the resolution and type of long-term TC record."

Something yet unknown has orchestrated the ebbing and flowing of global TC activity over the past 5,000 years. We do know it has not been changes in the atmosphere's CO_2 concentration, which has remained relatively stable over this entire period except for the past 100 years, when it has risen substantially without any demonstrable change in global TC activity. There is no compelling reason to believe further increase in the air's CO_2 content will have any significant impact on these destructive storms.

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