6

Observations: The Hydrosphere and Ocean

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Introduction

The hydrosphere comprises the combined mass of water that occurs on or near Earth’s surface. It includes oceans, lakes, rivers, and streams. Because it covers about 70 percent of Earth’s surface area, the hydrosphere plays a vital role in sustaining communities of water-inhabiting plants and animals.

The processes and characteristics of the hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, aspects of the hydrosphere also change in response to external climate change forcings, some of which are natural (e.g., changed solar insolation) and some of human origin (e.g., greenhouse gas forcing). This distinction between natural and anthropogenic forcings, which applies to all aspects of Earth’s climate system, is easy to draw in principle, but in practice it has proved difficult to establish that any specific changes documented in the hydrosphere over the past century have their origins in human activity.

Near Earth’s surface, precipitation of water out of the atmosphere occurs mostly in the forms of rain and snow. Hail contributes locally when conditions of strong, upward motion and freezing at lower levels of the atmosphere occur within passing thunderstorms and result in the formation of ice balls and lumps. The Northern and Southern Hemisphere monsoons are also precipitation-related phenomena, representing periods of particularly intense rainfall driven by strong, seasonal, wind-induced movements of moisture-laden air off the ocean and onto an adjacent landmass.

At the same time, the patterns of evaporation that recycle water back to the atmosphere are heavily dependent upon both atmospheric and ocean temperature, which themselves vary in dynamic ways. Evaporation and precipitation are key processes that help determine the occurrence of rare meteorological events such as the storm bursts, cyclones, and deluges that feed catastrophic (from the human perspective) flooding; alternatively, the absence of precipitation can lead to equally catastrophic dryings and droughts.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC, 2007) paid much attention to the possibility human greenhouse-induced warming would lead to an increase in either or both the number and severity of extreme meteorological events. Subsequently, however, an IPCC expert working group (IPCC, 2012) has determined:

> There is medium evidence and high agreement that long-term trends in normalised losses have not been attributed to natural or anthropogenic climate change. … The statement about the absence of trends in impacts attributable to natural or anthropogenic climate change holds for tropical and extratropical storms and tornados. … The absence of an attributable climate change signal in losses also holds for flood losses.

This chapter, building on the earlier conclusions of Idso and Singer (2009) and Idso *et al.* (2011), updates the Nongovernmental International Panel on Climate Change's (NIPCC) summary of the scientific literature on global warming as it might affect the hydrosphere. We again find changes in evaporation, precipitation, drought, ocean heat, ocean circulation, and sea level occur mostly in ways that contradict and rarely reinforce the claims of the IPCC and the projections of its models. Contrary to what has been feared would be caused by rising carbon dioxide levels, over the past 50 years there have been no CO_2-linked changes in precipitation patterns or river flows; signs exist of deceleration rather than acceleration of sea-level rise; and there have been no unnatural changes in the rate or pattern of Atlantic meridional overturning circulation (MOC).

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6.1 The Hydrosphere

Key Findings

There appears to be nothing unusual about the extremes of wetness and dryness experienced during the twentieth century, or about recent changes in ocean circulation, sea level, or heat content, that would require atmospheric carbon dioxide forcing to be invoked as a causative factor. Natural variability in the frequency or intensity of precipitation extremes and sea-level change occurs largely on decadal and multidecadal time scales, and this variability cannot be discounted as a major cause of recent changes where they have occurred.

The main findings of Section 6.1, The Hydrosphere, are:

- GLOBAL PRECIPITATION. Theoretical climate models indicate atmospheric moisture will be enhanced in a warming world, and therefore global precipitation should have increased in the late twentieth century. Although the empirical evidence is not fully conclusive, it increasingly indicates no temperature-related intensification of the hydrological cycle has occurred recently over the global land surface.

- REGIONAL PRECIPITATION. From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events such as floods and droughts. Regional studies from around the world in general fail to provide evidence of rising or more variable precipitation in the late twentieth century. These studies also show (1) ancient floods or droughts of at least the same magnitude as their modern counterparts occurred repetitively throughout the Holocene (last 10,000 years) and before; (2) decreased rainfall occurred during both climatically warm (Medieval Warm Period) and climatically cool (Little Ice Age) periods; (3) warming is sometimes accompanied by a reduction in precipitation-related weather extremes; (4) no evidence exists for a correlation between precipitation variability and atmospheric levels of CO_2; instead, studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, El Niño-Southern Oscillation, and solar variation implicated as controlling factors.

- WATER RESOURCES. Concern has been expressed that increasing concentrations of atmospheric CO_2 will adversely affect water resources. Nearly all water resource studies show just the opposite occurred during the late twentieth century warming, with moisture becoming more available.

- MONSOONS. Evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. Instead, the data sometimes suggest the opposite and overall suggest precipitation responds mostly to cyclical variations in solar activity. Both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period.

- MONSOON MODELS. Assessments of the predictive skill of monsoon models forced by CO_2 change unanimously find them to be inadequate. If climate models cannot accurately simulate the monsoonal precipitation that affects almost half the world's population, they cannot be relied upon as a basis for setting policy. A better understanding of the role of internal feedback processes as represented by the ENSO, PDO, AMO, solar, and other climatic indices is needed for improved forecasting of monsoon behavior.

- SNOWFALL. Studies from China above 40°N latitude demonstrate late twentieth century warming was accompanied by an increase in winter snow depth, promoting increased vegetative growth in desert areas and grasslands and resulting in a reduction in sand-dust storms. These changes represent environmentally positive developments.

- EVAPORATION. Theoretical considerations suggest late twentieth century warming should have been accompanied by an increase in evaporation. Instead, direct measurements of pan evaporation show a reduction over the twentieth century. This reduction has been linked to reducing insolation (solar dimming) and wind stilling at ground level, caused by increasing cloud cover and atmospheric aerosols.

- DROUGHT. Drought represents moisture deficit, but the relationship between the occurrence of drought and global warming is, at best, weak. In some places severe droughts occurred during the Medieval Warm Period, and in others severe droughts failed to occur during the late twentieth century warming. The evidence suggests the recent warming in particular, and drought in general, are the result of factors other than anthropogenic CO_2 emissions.

- STREAMFLOW. Many authors claim global warming will lead to the intensification of the hydrological cycle and the global occurrence of more floods. Few real-world data support this speculation. Neither global nor regional changes in streamflow can be linked to CO_2 emissions. Moreover, most recent changes in streamflow have been either not deleterious or beneficial—often extremely so. Some studies have identified solar factors or multidecadal cyclicity as more important influences on streamflow variability than is atmospheric CO_2.

6.1.1 Precipitation

All forms of precipitation are dynamic, occurring or not occurring in response to changing atmospheric conditions (especially heat and water vapor) on a minute-by-minute, hourly, daily, weekly, or seasonal basis. Regarding the potential effect of global warming on these patterns, Huntington (2006) has noted 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).” In reviewing the scientific literature on recent patterns of precipitation, Huntington concluded on a globally averaged basis, precipitation over land had indeed increased by about 2 percent over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998).

In keeping with this result, model predictions of CO_2-induced global warming often suggest warming should be accompanied by increases in rainfall. For example, Rawlins *et al.* (2006) state, after the *Arctic Climate Impact Assessment* (2005), “warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation.” Peterson *et al.* (2002) noted “both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature,” citing Manabe and Stouffer (1994) and Rahmstorf and Ganopolski (1999). Similarly, Kunkel (2003) says “several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998).” To date, global circulation models (GCMs) have failed to accurately reproduce observed patterns and totals of precipitation (Lebel *et al.*, 2000).

Moise *et al.* (2012) analyzed the changes in tropical Australian climate projected by 19 CMIP3 coupled models for the IPCC’s A2 scenario over the twenty-first century. While equatorial regions to the north of Australia are projected to have increased precipitation during austral summer (December to February) by the end of the twenty-first century, there is no significant change over northern Australia itself, based on the model ensemble mean. There is a large spread in model simulations of precipitation change, with both large positive and negative anomalies. The ensemble mean change in the seasonal cycle of precipitation over tropical Australia is nonetheless small, with precipitation increase during March and April, suggesting a prolonged Australian wet season.

No model consensus exists on how interannual variability of tropical Australian precipitation will change in the future, although more models simulate increased variability than decreased. Correlations between full wet season (October to April) precipitation and austral spring (September to November) NINO 3.4 sea surface temperature anomalies show a slight weakening. The spread in projected precipitation seasonal cycle changes between simulations from the same model is larger than the inter-model range, indicating large internal or natural variability in tropical Australian precipitation relative to the climate change signal. Zonal wind changes indicate an intensification of austral summer low level westerlies combined with a weakening of upper easterlies. Low level westerlies also persist for longer periods of time, consistent with a delay in the monsoon retreat.

All models simulate an increase in the land-ocean temperature contrast in austral summer, with a significant correlation between changes in land-ocean temperature contrast in the pre-monsoon (austral spring) and summer precipitation changes. Analysis of precipitation changes using regime-sorting techniques shows offsetting tendencies from thermodynamic changes associated with enhanced atmospheric moisture and dynamic changes associated with a weakened atmospheric circulation.

Conclusions

We are thus confronted with a dilemma: Although the theoretical expectation, supported by modeling, is that global warming should result in enhanced atmospheric moisture, empirical results often show otherwise. Many scientists are now examining historical precipitation records in an effort to determine how temperature changes of the past have affected Earth’s hydrologic cycle. In the following sections, we review what these studies have revealed about patterns of precipitation, region by region across the globe.

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6.1.1.1. Global

From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events, such as floods and droughts. Nonetheless, some researchers have attempted to address the issue at a global level, as represented by the following studies.

New *et al.* (2001) reviewed several global precipitation datasets and summarized precipitation patterns since the late nineteenth century. They determined precipitation over land fell mostly below the century-long mean over the first 15 years of the record but increased from 1901 to the mid-1950s, remained above the century-long mean until the 1970s, and declined by about the same amount thereafter up to 1992 (taking it well below the century-long mean), before recovering to edge upward towards the century mean. For the entire century there was a slight increase in global land area precipitation, but after 1915 there was essentially no net change.

New *et al.* also studied the oceanic portion of the world between 30°N and 30°S, the precipitation record for which begins in 1920. They found an overall decrease of about 0.3 percent per decade. For the planet as a whole, which is 70 percent covered by water, there probably has been a slight decrease in precipitation since about 1917.

Neng *et al.* (2002) analyzed more recent precipitation data, from 1948 to 2000, to determine the effect of warm ENSO years on annual precipitation over the land area of the globe. Although some regions experienced more rainfall in warm ENSO years, others experienced less. "In warm event years, the land area where the annual rainfall was reduced is far greater than that where the annual rainfall was increased, and the reduction is more significant than the increase." This result conflicts with GCM model projections.

Smith *et al.* (2006) used empirical orthogonal function (EOF) analysis to study annual precipitation variations over 26 years beginning in 1979 using a database from the Global Precipitation Climatology Project (GPCP), which produces a merged satellite and *in situ* global precipitation estimate (Huffman *et al.*, 1997; Adler *et al.*, 2003). The first three EOFs determined accounted for 52 percent of the observed variance in the precipitation data. Mode 1 was associated with mature ENSO conditions and correlated strongly with the Southern Oscillation Index, whereas Mode 2 was associated with the strong warm ENSO episodes of 1982/83 and 1997/98. Mode 3 was uncorrelated with ENSO but associated with changes in interdecadal warming of tropical sea surface temperatures, including increased precipitation over the tropical Pacific and Indian Oceans associated with local ocean warming. This increased precipitation was "balanced by decreased precipitation in other regions," so "the global average change [was] near zero."

Ault *et al.* (2012) summarized the application of GCMs to precipitation analysis, acknowledging "the last generation of models, those comprising [the] Climate Model Intercomparison Project III (CMIP3) archive, was unable to capture key statistics characterizing decadal to multidecadal (D2M) precipitation fluctuations" and "CMIP3 simulations overestimated the magnitude of high frequency fluctuations and consequently underestimated the risk of future decadal-scale droughts.

Ault *et al.* then used the Climate Model Intercomparison Project 5 (CMIP5) network to evaluate the ability of these models to simulate twentieth century variability. Their analyses were conducted using gridded (2.5 x 2.5) version 4 reanalysis product data available from the Global Precipitation Climatology Centre (Rudolf *et al.*, 2005), which spans the period January 1901 through December 2007. They found "CMIP5 simulations of the historical era (1850–2005) underestimate the importance [of] D2M variability in several regions where such behavior is prominent and linked to drought," namely, "northern Africa (e.g., Giannini *et al.*, 2008), Australia (Kiem and Franks, 2004; Verdon *et al.*, 2004; Leblanc *et al.*, 2012), western North America (Seager, 2007; Overpeck and Udall, 2010), and the Amazon (Marengo *et al.*, 2011)."

Ault *et al.* further state "the mismatch between 20th century observations and simulations suggests model projections of the future may not fully represent all sources of D2M variations," noting "if observed estimates of decadal variance are accurate, then the current generation of models depict D2M precipitation fluctuations that are too weak, implying that model hindcasts and predictions may be unable to capture the full magnitude of realizable D2M fluctuations in hydroclimate." As a result, "the risk of prolonged droughts and pluvials in the future may be greater than portrayed by these models."

Sun *et al.* (2012) analyzed monthly precipitation observations from 1940–2009 for the global land surface, having assessed the ocean precipitation data as unreliable for trend analyses. They found a near-zero trend in decadal mean precipitation, a finding consistent with earlier studies that found little variation in global mean precipitation at periods longer than the turnover time for water in the atmosphere (~10 days). They did, however, find a reduction in the global land precipitation variation, such that wet areas became drier and dry areas became wetter. This finding directly contradicts the expectation (Section 6.1.6) that there would be an intensification of the hydrological cycle (i.e., wet areas get wetter and dry areas get drier as stated by Trenberth (2011). Sun *et al.* also found, with respect to monthly precipitation variance (an indicator of extreme precipitation), there was "no relationship to local … or global changes in temperature."

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Earlier Research

Other important studies of rainfall changes, at the regional rather than global level, include the following:

- Stankoviansky (2003) used maps, aerial photographs, field geomorphic investigation, and historical documentation to determine the spatial distribution and history of gully landforms in Myjava Hill Land, Slovakia (near the Czech Republic western border). Stankoviansky 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 between the 1780s and 1840s. Though gullying was caused by the extensive forest clearances undertaken to expand farmland, the triggering mechanism was extreme rainfalls during the Little Ice Age." Stankoviansky concluded "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"; he also noted destructive rainfall events were much more common during the Little Ice Age than thereafter "is often regarded as generally valid for Central Europe." In other words, this empirical evidence shows cooling rather than warming results in greater precipitation.
- Giambelluca *et al.* (2008) and Chu *et al.* (2010) undertook assessments of whether warming at a rate of 0.163°C/decade, as experienced recently in Hawaii, was associated with additional rainfall. Five climate change indices for extreme precipitation were calculated from daily observational records between the 1950s and 2007: a simple daily intensity index, the total number of days with precipitation ≥25.4 mm, the annual maximum consecutive five-day precipitation amount, the fraction of annual total precipitation from events that exceeded the 1961–1990 95th percentile, and the number of consecutive dry days. Chu *et al.* documented a change in the types of precipitation intensity since the 1980s, with more frequent light precipitation and less frequent moderate and heavy precipitation, as well as a "shorter annual number of days with intense precipitation and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events

exceeding the 1961–1990 95th percentile in the recent epoch [1980–2007] relative to the first epoch [1950–1979].” IPCC predictions for more precipitation to occur with Hawaiian warming are incorrect; in fact, the opposite occurred.

- Diodato *et al.* (2008) studied erosive rainfall in the Calore River Basin (Southern Italy) using combined data from 425-year-long series of observations (1922–2004) and proxy-based reconstructions (1580–1921). Interdecadal variability was strong, with multidecadal erosional peaks reflecting the behavior of the mixed population of thermo-convective and cyclonic rainstorms that occurred. Like Stankoviansky (2003), they found the “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.”
- Xu *et al.* (2008) analyzed 50 years (1957–2006) of upper-air Chinese radiosonde observations, along with parallel surface air temperature and precipitation data. In the summer half of the year, they found, “the Tibetan Plateau acts as a strong ‘dynamic pump’ [that] continuously attracts moist air from the low-latitude oceans.” When reaching the plateau, some of these flows rise along its south side and cause “frequent convections and precipitations,” which feed its mid- and low-latitude glaciers, snow-packs, and lakes, from whence originate many of Asia’s major rivers. This flow system constitutes the largest river runoff from any single location in the world. The Tibetan Plateau has been called the “world’s water tower” because of the strong influence it exerts on northern hemisphere mid-latitude moisture, precipitation, and runoff.

In further analysis of their datasets, the four researchers found recent warming in the plateau started in the early 1970s, and the water vapor content showed an upward trend from the early 1980s and continues to the present time, a pattern similar to that found in the annual precipitation data.

- A longer climate history for the Tibetan Plateau for the past 1,700 years was developed by Zhao *et al.* (2009) based upon carbonate percentages and ostracod abundances in sediment cores from Hurleg Lake in the arid Northeast Tibetan Plateau. They compared those records with a contemporaneous history of precipitation derived from tree-ring analysis and changes in solar activity manifest in solar proxy residual Δ^{14}C data.

Zhao *et al.* discovered carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the past 1,000 years. Cross-spectral analysis between the moisture proxies and solar activity proxy showed high coherence at the ~200-year periodicity. This correlation also is found with Chinese monsoon intensity records and implies the possible solar forcing of moisture oscillations in the NE Tibetan Plateau. In addition, the inverse relationship between the moisture pattern in the Qaidam Basin and tree-ring-based monsoon precipitation in the surrounding mountains suggests “topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region.”

- Kim *et al.* (2009) analyzed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006) to assess drought severity using four indices: the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), described as “an intensive measure that considers daily water accumulation with a weighting function for time passage”; a Corrected EDI (CEDI) that “considers the rapid runoff of water resources after heavy rainfall”; an Accumulated EDI (AEDI) that “considers the drought severity and duration of individual drought events”; and a year-accumulated negative EDI (YAEDI) “representing annual drought severity.”

The researchers’ precipitation history and two of their drought severity histories are presented, in that order, in Figures 6.1.1.1.1 and 6.1.1.1.2. It is apparent the only major deviation from long-term normality is the decadal-scale decrease in precipitation and ensuing drought around AD 1900. Neither the last part of the Little Ice Age during the early nineteenth century nor the onset of high carbon dioxide emissions after about 1950 appears to exercise any effect on precipitation or drought in Korea, and similar results are known from around the world.

Conclusions

Although Huntingdon (2006) concluded the evidence on balance was consistent with an ongoing and future intensification of the global hydrological cycle, he acknowledged considerable uncertainties and noted the evidence did not support the likelihood of increasingly frequent and intense tropical storms and floods. Since his review, the evidence remains mixed but increasingly indicates no temperature-related intensification of the hydrological cycle has been observed for the global land surface. Although the data show no global trend indicative of land precipitation intensification, spatial and temporal variations can result in regional trends.

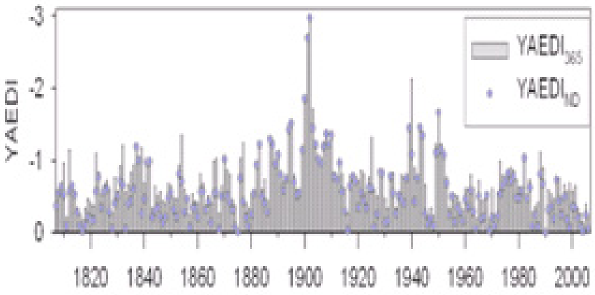

Figure 6.1.1.1.1. Annual "dryness" history at Seoul, Korea, 1807-2006, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., 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.

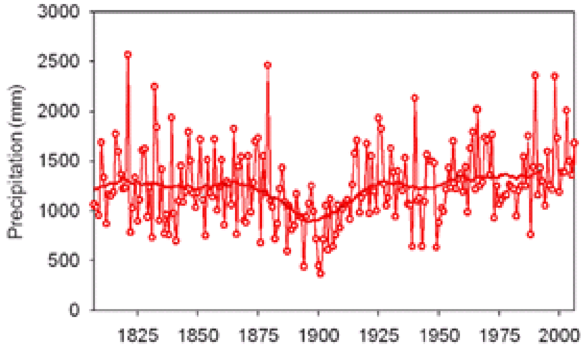

Figure 6.1.1.1.2. Annual precipitation history at Seoul, Korea; solid line, 30-year moving-average. Adapted from Kim *et al.* (2009).

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6.1.1.2. Africa

South Africa has one of the most comprehensive hydro-meteorological databases in the world. Remarkably, 40 years before the establishment of the IPCC, civil engineer D.F. Kokot (1948) published a report for the S.A. Department of Irrigation that found no evidence of a general decrease in the historical records of rainfall or river flow and concluded therefore no link existed between climate change and rainfall over South Africa, a conclusion confirmed by van der Merwe *et al.* (1951).

In the north of Africa another civil engineer, H.E. Hurst, analyzed 1,080 years of flow data from the Nile River for the period 641 to 1946 as part of storage capacity studies for the proposed Aswan High Dam (Hurst, 1951, 1954). He found an unexplained anomaly in the data, also present in other long meteorological (temperature, rainfall) and proxy (lake sediment cores, tree ring) records, which Alexander (1978) identified as related to a 20-year (later, 21-year) periodicity; i.e. to the Hale double sunspot cycle. It thereby became apparent South African periods of flood and drought occurred in a predictable way, rather than occurring at random as had been conventionally believed. The starts of drier and wetter periods are readily identified, characterized by sudden reversals from sequences of years with low rainfall (droughts) to sequences of years with wide-spread rainfall and floods. It is not the simple sum of annual sunspot numbers (Figure 6.1.1.2.1, top graph) that are in synchrony with river flows plotted as the annual departure from the mean (Figure 6.1.1.2.1, fourth graph), but rather the rate of change in sunspot numbers (Figure 6.1.1.2.1, second graph).

Will Alexander, professor of civil engineering at the University of Pretoria, later published several pivotal papers and reports (e.g., Alexander 1995, 2005, 2006; Alexander *et al.*, 2004) that greatly increased our understanding of flood-drought cycling in southern Africa and established the importance of solar influence. In his 1995 paper, published just before the end of the severe drought that accompanied cycle G, Alexander predicted the oncoming flood period (G).

Alexander points out nearly all previous analyses of rainfall patterns have been based on the assumption that data for annual rainfall, river flow, and flood peak maxima are independent, identically distributed, and form stationary time series. All three assumptions are wrong.

Detailed, high-quality hydrological datasets from South Africa show instead annual values are sequentially independent but not serially independent; sequential values are not identically distributed as both their mean values as well as their distribution about the mean change from year to year in 21-year sequences; and the series are not stationary in time because of the presence of statistically significant 21-year serial correlation. These properties are related to a synchronous linkage with solar activity, as first reported more than 100 years ago by Hutchins (1889). Later studies by Spate *et al.* (2004) and Whiting *et al.* (2004) also demonstrate flood spate flows in Southern Africa occur on a multidecadal rhythm closely linked to the El Niño-Southern Oscillation.

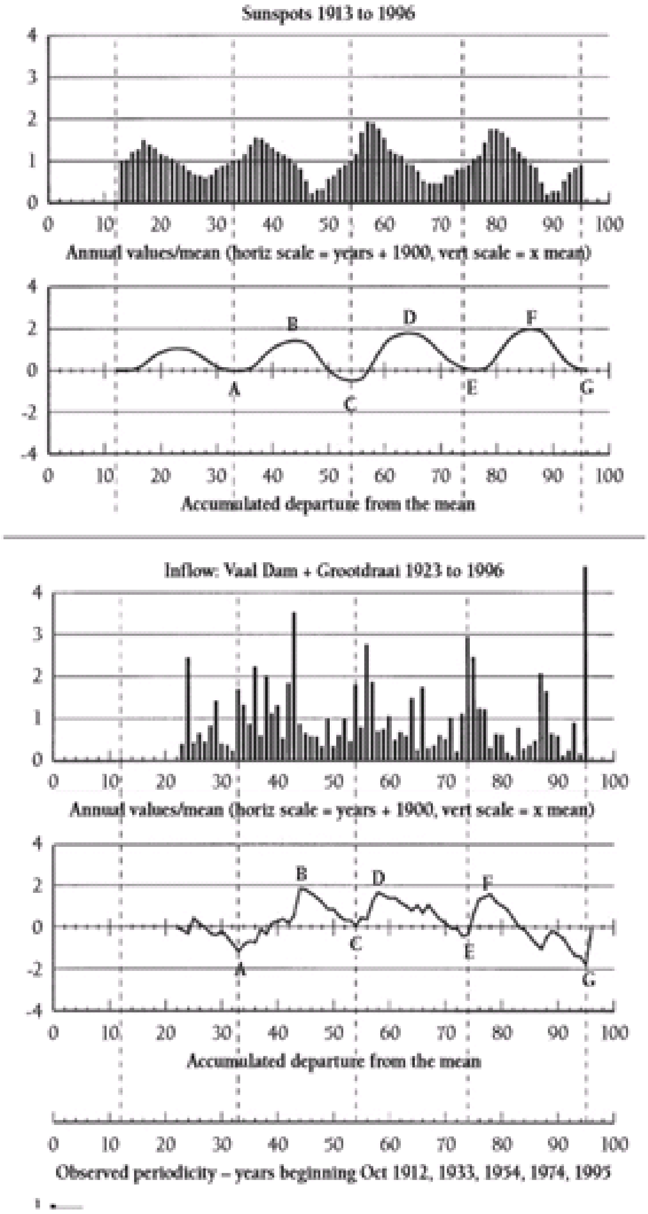

Figure 6.1.1.2.1. Comparison of the characteristics of annual sunspot numbers with corresponding characteristics of annual flows in the Vaal River, South Africa. Adapted from Alexander, W.J.R., Bailey, F., Bredenkamp, D.B., van der Merwe, A., and Willemse, N. 2007. Linkages between solar activity, climate practicability and water resource development. *Journal of the South African Institution of Civil Engineering* **49**: 32–44, Figure 7.

Conclusions

Alexander *et al.* (2007) explain the significance of this pivotal research:

> It is extremely important that all those involved with water resource studies should appreciate that there are fundamental flaws in current global climate models used for climate change applications. These models fail to accommodate the statistically significant, multiyear periodicity in the rainfall and river flow data observed and reported by South African scientists and engineers for more than the past 100 years. They also failed to predict the recent climate reversals based on Alexander's model (Alexander 1995, 2005). The global climate model outputs can therefore not be used for adaptation studies.

Koutsoyiannis (2013) has argued the multiscale change in flow records in the Nile, first recorded by

Hurst and then further analyzed by Alexander and others, indicates long-term flow changes relevant to water engineering are much more frequent and intense than commonly perceived. Accordingly, future system states are much less certain and predictable on long time scales than is implied by standard methods of statistical analysis. From Koutsoyiannis argues a change of perspective is needed, in which change and uncertainty form essential parts of future hydrological analyses.

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Earlier Research

Other significant recent papers on African precipitation patterns include the following:

- In two contextual studies, Lee-Thorp *et al.* (2001) described repeated rapid climate shifts in Southern Africa since the middle Holocene, and Verschuren *et al.* (2000) examined hydrologic conditions in equatorial East Africa over the past one thousand years. Verschuren *et al.* report the region was significantly drier than today during the Medieval Warm Period (AD 1000–1270) and relatively wetter than today during the Little Ice Age (AD 1270–1850). The LIA wetting was interrupted by three episodes of drought in 1390–1420, 1560–1625, and 1760–1840, which were “more severe than any recorded drought of the twentieth century.”
- The late eighteenth/early nineteenth century dry period in East Africa also was identified in West Africa by Nicholson (2001). She reports the most significant climatic change over the past 200 years has been “a long-term reduction in rainfall in the semi-arid regions of West Africa,” by as much as 20 to 40 percent in parts of the Sahel. There have been, she says, “three decades of protracted aridity” and “nearly all of Africa has been affected ... particularly since the 1980s.” Nicholson further notes dry conditions similar to those that have affected nearly all of Africa since the 1980s are not unprecedented; “a similar dry episode prevailed during most of the first half of the 19th century.”
- Nicholson and Yin (2001) report there have been two starkly contrasting climatic episodes in equatorial East Africa since the late 1700s. The first, which began prior to 1800, was characterized by “drought and desiccation.” Extremely low lake levels were the norm as drought reached its extreme during the 1820s and 1830s. In the mid to latter part of the 1800s, the drought began to weaken and floods became “continually high.” By the turn of the century, lake levels began to fall as mild drought conditions returned. The drought did not last long, and the latter half of the twentieth century has seen an enhanced hydrologic cycle with a return of some lake levels to the high stands of the mid to late 1800s.
- Richard *et al*. (2001) analyzed summer (January-March) rainfall totals in southern Africa over the

period 1900–1998, finding interannual variability was higher for the periods 1900–1933 and 1970–1998 but lower for the period 1934–1969. The strongest rainfall anomalies (greater than two standard deviations) were observed at the beginning of the century. The authors conclude there were no significant changes in the January-March rainfall totals nor any evidence of abrupt shifts during the twentieth century.

Conclusions

Three conclusions can be drawn from the African rainfall data.

- The recent much-commented recent drying in the Sahel is not in itself evidence of human-caused warming, because similar dry periods occurred periodically during the recent past.
- There is no established relationship between rainfall trends or changes in Africa and increased atmospheric carbon dioxide during the second half of the twentieth century.
- Contrary to some climate model projections, decreased rainfall can occur during both climatically warm (MWP) and climatically cool (LIA) times.

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6.1.1.3. Mediterranean

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Mediterranean region include the following:

- Rodrigo *et al.* (2000, 2001) reconstructed a seasonal rainfall record for 1501–1997 for Andalusia (southern Spain), and established a relationship exists with the North Atlantic Oscillation (NAO) over the period 1851–1997. Their research established the NAO index correlation with climate is strongest in winter, when it explains 40 percent of the total variance in precipitation. Rodrigo *et al.* stress "the recent positive temperature anomalies over western Europe and recent dry winter conditions over southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s," as opposed to an intensification of global warming.
- Crisci *et al.* (2002) analyzed rainfall data from 81 gauges throughout Tuscany (central Italy) for three periods: from the beginning of each record through 1994; a shorter 1951–1994 period; and a still-shorter 1970–1994 period. For each of these periods, trends were derived for extreme rainfall durations of 1, 3, 6, 12, and 24 hours.

For the period 1970–1994, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested. For the longer 1951–1994 period, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations and one had negative trends at all durations. For the still-longer complete period of record, the majority of all stations again exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations, and one had negative trends at all durations. Such global warming as may have occurred during the twentieth century clearly had no impact on Italian rainfall.

- Tomozeiu *et al.* (2002) performed a series statistical tests to investigate the nature and potential causes of trends in winter (December–February) mean precipitation recorded at 40 stations in Northern Italy over the period 1960–1995. Nearly all stations experienced significant decreases in winter precipitation over the 35-year period of study, and a Pettitt test indicated a significant downward shift at all stations around 1985. An Empirical Orthogonal Function analysis revealed a principal component representing the North Atlantic Oscillation (NAO), as found also by Rodrigo *et al.* (2001), suggesting the changes in winter precipitation around 1985 "could be due to an intensification of the positive phase of the NAO."

- Sousa and Garcia-Murillo (2003) studied proxy indicators of climatic change, including precipitation, in Doñana Natural Park in Andalusia (southern Spain) for a period of several hundred years and compared their results with those of other researchers. The work revealed the Little Ice Age (LIA) was non-uniform and included periods both wetter and drier than average. Nevertheless, they cite Rodrigo *et al.* (2000) as indicating "the LIA was characterized in the southern Iberian Peninsula by increased rainfall" and Grove (2001) as indicating "climatic conditions inducing the LIA glacier advances [of Northern Europe] were also responsible for an increase in flooding frequency and sedimentation in Mediterranean Europe." Sousa and Garcia-Murillo's research complements the others' work, finding "an aridization of the climatic conditions after the last peak of the LIA (1830–1870)," suggesting much of Europe became drier, not wetter, as Earth passed out of the Little Ice Age.
- Alexandrov *et al.* (2004) analyzed a number of twentieth century datasets from throughout Bulgaria and found "a decreasing trend in annual and especially summer precipitation from the end of the 1970s"; they note "variations of annual precipitation in Bulgaria showed an overall decrease." In addition, the region stretching from the Mediterranean into European Russia and the Ukraine "has experienced decreases in precipitation by as much as 20% in some areas."
- Touchan *et al.* (2005) used tree-ring data to develop summer (May–August) precipitation reconstructions for eastern Mediterranea (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back as much as 600 years. The research showed summer precipitation varied on multiannual and decadal timescales but without any overall long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods in 1601–1605 and 1751–1755. Both extreme wet and dry precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930.
- Clarke and Rendell (2006) analyzed 50 years of rainfall records (1951–2000) from eastern Basilicata (southern Italy) and compared them with the occurrence of floods and landslides. They found "the frequency of extreme rainfall events in this area declined by more than 50% in the 1990s compared to the 1950s." In addition, the "impact frequency also decreased, with landslide-event frequency changing from 1.6/year in the period 1955–1962 to 0.3/year from 1985 to 2005, while flood frequency peaked at 1.0/year in the late 1970s before declining to less than 0.2/year from 1990." If the climate-driven changes that occurred over the latter part of the twentieth century continue, Clarke and Rendell conclude, "the landscape of southern Italy and the west-central Mediterranean will become increasingly stable."

Conclusions

Several studies from the Mediterranean region show summer precipitation in the eastern Mediterranean became less variable as late twentieth century warming occurred than it had been in the earlier part of the century or in previous centuries. None of the Mediterranean studies provides evidence for the rising or more variable precipitation in the late twentieth century predicted by global climate models.

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6.1.1.4 Central Europe

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Central Europe include the following:

- Koning and Franses (2005) analyzed a century of daily precipitation data for the Netherlands, acquired at the de Bilt meteorological station in Utrecht. Using robust nonparametric techniques, they found the cumulative distribution function of annual maximum precipitation levels of rainfall remained constant throughout the period 1906–2002, leading them to conclude “precipitation levels are not getting higher.” The authors also report similar analyses performed for the Netherlands’ five other standard meteorological stations “did not find qualitatively different results.”
- Wilson *et al.* (2005) developed two March–August precipitation chronologies for the Bavarian Forest of southeast Germany, based on tree-ring widths obtained for the period 1456–2001. The first chronology, standardized with a fixed 80-year spline function (SPL), was designed to retain decadal and higher frequency variations; the second used regional curve standardization (RCS) to retain lower frequency variations. The SPL chronology failed to reveal any significant yearly or decadal variability, and there did not appear to be any trend toward either wetter or drier conditions over the 500-year period. The RCS reconstruction, by contrast, capturing lower frequency variation better, showed March–August precipitation was substantially greater than the long-term average during the periods 1730–1810 and 1870–2000 and less than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870. The found little evidence of a long-term trend, however, or of any relationship to accumulating CO_2 emissions.
- Solomina *et al.* (2005) derived the first spring (April–July) tree-ring reconstruction for the period 1620–2002 for the Crimea Peninsula (Ukraine). This chronology was correlated with an earlier precipitation reconstruction derived from a sediment core taken in 1931 from nearby Saki Lake, providing a proxy precipitation record for the region that stretches back 1,500 years to AD 500. A parallel instrumental record from near the tree-sampling site shows no trend in precipitation over about the past century (1896–1988).

  The reconstructed precipitation values from the tree-ring series revealed year-to-year and decadal variability but were near-average with relatively few extreme values between about the middle 1700s and the early 1800s, and again since about 1920. The most notable anomaly of the 1,500-year reconstruction was an “extremely wet” period between AD 1050 and 1250, which Solomina *et al.* describe as broadly coinciding with the Medieval Warm Period, when humidity was higher than during the instrumental era.
- Zanchettin *et al.* (2008) demonstrated rainfall variability across Europe is influenced by the interaction of NAO, ENSO, and the PDO. Multidecadal variability in these indices may produce nonstationary rainfall variability on multidecadal timescales.

Conclusions

These studies demonstrate enhanced precipitation did not occur in Central Europe during the twentieth century global warming.

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6.1.1.5. Boreal

Earlier Research

Earlier Boreal research concerning the relationship between precipitation and climate change include the following papers:

- Hanna *et al.* (2004) analyzed variations in several climatic variables in Iceland over the past century, including precipitation. For the period 1923–2002, precipitation appeared to have increased slightly, although they question the veracity of the trend citing several biases that may have corrupted the data base.
- 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. This work revealed a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record. Over the past century of supposedly unprecedented global warming, however, precipitation was found to have exhibited less variability than it did during the preceding 150 years.
- Linderholm and Chen (2005) derived a 500-year winter (September–April) precipitation chronology using tree-ring data obtained from the forest zone of west-central Scandinavia. Their record exhibited considerable variability except for a fairly stable period of above-average precipitation between AD 1730 and 1790. Above-average winter precipitation also was found to have occurred in 1520–1561, 1626–1647, 1670–1695, 1732–1851, 1872–1892, and 1959 to the present, with the highest values reported in the early to mid-1500s. Below-average winter precipitation was observed during 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 the beginning of the seventeenth century.

Conclusions

These findings demonstrate conditions irregularly alternating between wetter and drier than the present have occurred repeatedly within the Boreal region throughout the past five centuries, with no particular sign of an additional influence from carbon dioxide emissions in the late twentieth century. Similar conditions can be expected to recur naturally in the future.

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6.1.1.6. Arctic

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Arctic region include the following:

- Curtis *et al.* (1998) examined a number of climatic variables at two first-order Arctic weather stations (Barrow and Barter Island, Alaska) from records that began in 1949. Both the frequency and mean intensity of precipitation decreased at these stations over the period of record. Though temperatures in the western Arctic increased over this period, "the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere." The four researchers conclude the theoretical model-based assumption that "increased temperature leads to high precipitation ... is not valid," at least for the part of the western Arctic that was the focus of their study.
- Lamoureux (2000) analyzed varved sediments from Nicolay Lake, Cornwall Island, Nunavut, Canada, comparing them with rainfall events recorded at a nearby weather station over the period 1948–1978. A rainfall history was established for the region over the 487-year period 1500–1987. The record was suggestive of a small, statistically insignificant increase in rainfall over the period. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic as well as the Arctic as a whole. Lamoureux also found "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic

types during the coldest periods of the Little Ice Age."

- Rawlins *et al.* (2006) calculated trends in the averaged water equivalent of annual rainfall and snowfall for 1936–1999 across the six largest Eurasian drainage basins that feed major rivers delivering water to the Arctic Ocean. The annual rainfall across the total area of the six basins decreased consistently and significantly over the 64-year period. Annual snowfall, by contrast, underwent a strongly significant increase until the late 1950s. Thereafter, snowfall declined, and "no significant change [was] determined in Eurasian-basin snowfall over the entire 64-year period." Overall, annual total precipitation (rainfall and snowfall) decreased over the period of this study. The authors report their finding is "consistent with the reported (Berezovskaya *et al.*, 2004) decline in total precipitation."

Conclusions

These studies, and especially that of Lamoureux (2000), show the late twentieth century warming was accompanied by a *reduction* in the number of weather extremes related to precipitation in a part of the planet predicted to be most affected by CO_2-induced global warming, the Canadian High Arctic.

Thus we can conclude either the theoretical arguments and model predictions that suggest "high-latitude precipitation increases in proportion to increases in mean hemispheric temperature" are not robust; or late twentieth century temperatures were not warmer than those of the mid-1930s and '40s; or both of the above. All three conclusions fail to provide support for a key claim of the *Arctic Climate Impact Assessment* (2005).

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6.1.1.7. United States

For the most part, droughts in the United States have become shorter, less frequent, and less severe over the past century, and they have covered smaller areas (Figure 6.1.1.7.1).

Chen *et al.* (2012) set out to test the prediction that an increase in air temperature would result in higher evapotranspiration, thereby reducing available water and causing drought (IPCC, 2007; Karl *et al.*, 2009). Though the basis for the prediction is unsound, the test nonetheless revealed important results about the standard precipitation index (SPI) in relation to drought intensity for the Southern United States for 1895–2007. Chen *et al.* found "no obvious increases in drought duration and intensity during 1895–2007" and "no obvious increase in air temperature for the entire SUS during 1895–2007."

Conclusions

Once again, predictions made by the IPCC (2007) and the authors of the U.S. climate report of 2009 (Karl *et*

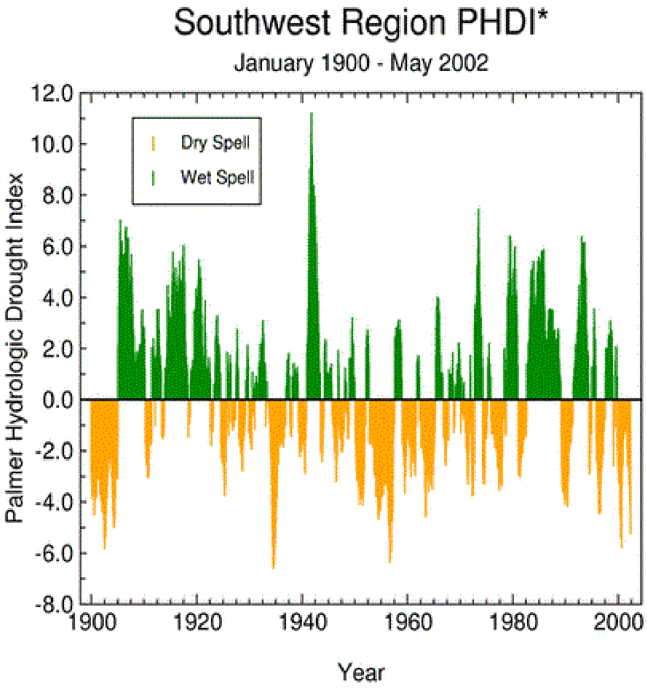

Figure 6.1.1.7.1. Drought Index for the southwestern US, 1900–2002. National Climatic Data Center, National Environmental Satellite, Data, and Information Service, National Oceanographic and Atmospheric Administration, http://www.ncdc.noaa.gov/sotc/drought/2002/5#paleo.

al., 2009), who warn of intensification of the hydrological cycle with increasing severity of extremes, are found to be without any confirmation in pertinent real-world data.

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Earlier Research

Earlier U.S. hydrological studies with respect to global warming include the following papers.

- Haston and Michaelsen (1997) used proxy tree-ring data to develop 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. Although regionwide precipitation during the twentieth century was higher than during the preceding three centuries, they found, it also was “less variable compared to other periods in the past.” However, Pierce *et al.* (2013) reviewed the results of 25 model projections of precipitation changes for California by 2060. They found 12 projected drier conditions and 13 projected wetter conditions, concluding California was likely to become drier, in contrast to the weak trend reported by Haston and Michaelsen.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. They detected a significant increasing trend in annual precipitation in the basin, driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range; at the same time, essentially no change occurred at the high-intensity end of the spectrum. For streamflow, no trend occurred at the annual timescale but monthly totals increased in low-flow months and decreased in high-flow months. No correlation exists between those changes and the CO_2 content of the atmosphere.
- Cronin *et al.* (2000) analyzed salinity gradients in sediment cores from Chesapeake Bay, the largest estuary in the United Sates, to determine precipitation variability in the surrounding watershed over the past 1,000 years. The authors identified a high degree of decadal and multidecadal variability between wet and dry conditions throughout the record, with inferred regional precipitation fluctuating by between 25 and 30 percent, often in “extremely rapid [shifts] occurring over about a decade.” Precipitation over the past two centuries was on average greater than during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the climate was judged to have been “extremely wet.” The researchers also determined this region, like the southwestern United States, had experienced several “mega-droughts” lasting from 60 to 70 years, some being “more severe than twentieth century droughts.”
- Cowles *et al.* (2002) analyzed snow-water equivalent (SWE) data for 1910–1988 obtained at more than 2,000 sites in the western United States using four measuring systems—snow courses, snow telemetry, aerial markers, and airborne gamma radiation. Though the whole-area trend in SWE was negative, significant differences from trend occurred in the southern Rocky Mountains where no change occurred with time. Cowles *et al.* note their results “reinforce more tenuous conclusions made by previous authors,” citing Changnon *et al.* (1993) and McCabe and Legates (1995), who studied snowpack data from 1951–1985 and 1948–1987, respectively, at 275 and 311 sites. They too found a decreasing trend in SWE at most sites in the Pacific Northwest but more ambiguity in the southern Rockies.
- Garbrecht and Rossel (2002) used state divisional monthly precipitation data from the U.S. National Climatic Data Center to investigate precipitation on the Great Plains from January 1895 through December 1999. The authors found regions in the central and southern Great Plains experienced above-average precipitation over the past two decades of the twentieth century, and this 20-year period marked the longest and most intense wet interval of the 105 years of record. The enhanced precipitation resulted primarily from a reduction in the number of dry years and an increase in the number of wet years. The number of very wet years did not increase as much and showed a decrease for many regions. The northern and northwestern Great Plains also

experienced a precipitation increase at the end of this 105-year interval, but it was primarily confined to the final decade of the twentieth century and again was marked by the occurrence of fewer dry years, not increased wet ones.

- McCabe and Wolock (2002) evaluated precipitation trends for the conterminous United States for 1895–1999. They considered annual precipitation minus annual potential evapotranspiration (net precipitation), surplus water that eventually becomes streamflow, and any water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. For the United States as a whole, they found a statistically significant increase in the first two of these three parameters, while for the third there was no change.
- Kunkel *et al.* (2003) also studied the conterminous United States, using a new database of daily precipitation observations for the period 1895–2000. The new data indicated heavy precipitation occurred more commonly during the late nineteenth and early twentieth centuries, decreased to a minimum in the 1920s and 1930s, and then increased into the 1990s. Kunkel *et al.* note "for 1-day duration events, frequencies during 1895–1905 are comparable in magnitude to frequencies in the 1980s and 1990s" and "for 5- and 10-day duration events, frequencies during 1895–1905 are only slightly smaller than late 20th century values."
- Ni *et al.* (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico using a network of 19 tree-ring chronologies. With respect to drought, they found "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 note the 1950s drought "was large in scale and severity, but it only lasted from approximately 1950 to 1956," whereas the sixteenth century megadrought lasted more than four times as long. With respect to rainfall, Ni *et al.* report several wet periods comparable to the wet conditions seen in the early 1900s and after 1976 occurred in "1108–20, 1195–1204, 1330–45, the 1610s, and the early 1800s." They also note "the most persistent and extreme wet interval occurred in the 1330s."

Regarding the causes of the precipitation extremes, Ni *et al.* state "the 1950s drought corresponds to La Niña/-PDO [Pacific Decadal Oscillation] and the opposite polarity [+PDO] corresponds to the post-1976 wet period." This led them to hypothesize that the prominent shifts seen in the 1,000-year precipitation reconstructions from Arizona and New Mexico may be linked to strong shifts in the coupled ENSO-PDO system.

- Using collated paleo-data, Verdon and Franks (2006) demonstrated PDO phases are significantly associated with changes in the frequency of both warm and cold ENSO events. This multidecadal variability of event frequency has marked implications for secular trends in U.S. climate, as also discovered by Ni *et al.* (2002).
- Gray *et al.* (2003) examined 15 tree-ring-width series used in previous reconstructions of drought for evidence of low-frequency variation in precipitation in five regions of the central and southern Rocky Mountains. They identified strong multidecadal phasing of moisture variation in all regions, a late sixteenth century megadrought, and showed "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." Like Ni *et al.* (2002), they note these changes "may ensue from coupling of the cold phase PDO [Pacific Decadal Oscillation] with the warm phase AMO [Atlantic Multidecadal Oscillation] (Cayan *et al.*, 1998; Barlow *et al.*, 2001; Enfield *et al.*, 2001)," something they envision happened in both the severe drought of the 1950s and the late sixteenth century megadrought.

Conclusions

Nearly all climate models suggest the planet's hydrologic cycle will be enhanced in a warming world and that precipitation should therefore have increased in the late twentieth century. This prediction is especially applicable to the Pacific Northwest of the United States, where Kusnierczyk and Ettl (2002) report climate models predict "increasingly warm and wet winters," as do Leung and Wigmosta (1999). As Cowles *et al.* (2002) show clearly, however, precipitation that fell and accumulated as snow in the western U.S. and Pacific Northwest during the late twentieth century was in fact reduced, not enhanced (see Figure 6.1.1.7.2).

Other studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, and El Niño-Southern Oscillation implicated as controlling factors.

Thus there appears to be nothing unusual about the extremes of wetness and dryness experienced

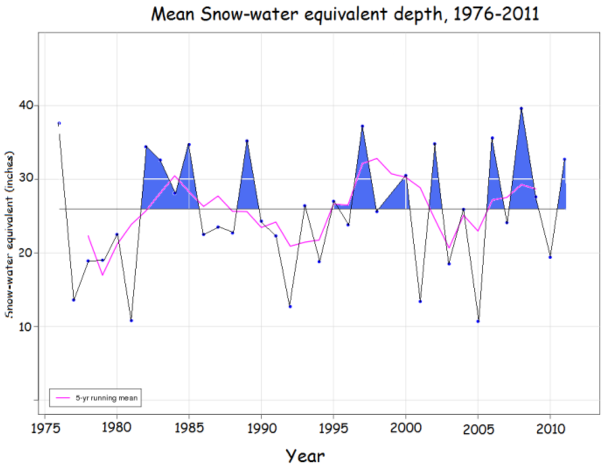

Figure 6.1.1.7.2. Mean snow accumulation in western USA, 1975-2011 (US National Resources Conservation Service, SNOTEL).

during the twentieth century that requires atmospheric CO_2 forcing to be invoked as a causative factor. In particular, several studies show frequencies of extreme precipitation events in the United States in the late 1800s and early 1900s were about as high as in the 1980s and 1990s. Natural variability in the frequency of precipitation extremes is large on decadal and multidecadal time scales and cannot be discounted as the cause or one of the causes of recent increases in precipitation where they have occurred.

Cronin *et al.*'s (2002) work, like the study of Ni *et al.* (2002), reveals nothing unusual about precipitation in the United States during the twentieth century, the last two decades of which the IPCC claims were the warmest of the past two millennia. Cronin *et al.*'s work indicates, for example, both wetter and drier intervals occurred repeatedly in the past in the Chesapeake Bay watershed. There is reason to believe such intervals will occur in the future with or without any further global warming.

Great concern has been expressed that increasing concentrations of carbon dioxide in the atmosphere will cause global warming that will in turn adversely affect water resources. The results of nearly all available U.S. studies reveal that during the twentieth century warming just the opposite has occurred: Moisture has become more available, and there has been no change in the amount of water required for optimum plant growth.

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6.1.1.8. Canada and Mexico

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Canada and Mexico include the following:

- Lamoureux (2000) analyzed varved lake sediments from Nicolay Lake, Cornwall Island, Nunavut (Canada), comparing the resulting climate history with the 1948–1978 rainfall history recorded at a nearby weather station. This enabled the construction of a rainfall history for the 487-year period between 1500 and 1987. No statistically significant increase in total rainfall was found to have occurred over period studied. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic and the Arctic as a whole. In addition, Lamoureux states, "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age."
- Zhang *et al.* (2001) also studied the history of heavy precipitation events across Canada, using "the most homogeneous long-term dataset currently available for Canadian daily precipitation." No significant long-term trends were apparent in the data, and decadal-scale variability was the dominant feature of both the frequency and intensity of the annual extreme precipitation events. Seasonal data, however, revealed an increasing trend in the number of extreme autumn snowfall events and precipitation totals (extreme plus non-extreme events) revealed a slightly increasing trend due to increases in the number of non-heavy precipitation events. Zhang *et al.* concluded "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."
- Diaz *et al.* (2002) created a 346-year history of winter-spring (November–April) precipitation for the Mexican state of Chihuahua, south of the U.S., using earlywood tree-ring width chronologies from 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. Diaz *et al.* found "three of the five worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century." Two of those three worst drought years occurred during a decadal period of average to slightly above-average precipitation, so the three years were not representative of long-term droughty conditions. The longest drought lasted 17 years (1948–1964), but for several of the years of that 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. Considering the twentieth century alone, a long period of high winter-spring precipitation stretched from 1905 to 1932 and, following the major drought of the 1950s, precip-itation remained at or just slightly above normal for the remainder of the record.

  No long-term trend is apparent over the full 346 years of record, nor is there any evidence of a significant departure from no-trend over the twentieth century. Consequently, and despite the spasmodic drought events described above, Chihuahua's precipitation history did not differ significantly during the twentieth century from what it was over the prior quarter of a millennium.
- The IPCC predicts global warming will produce

an increase in heavy precipitation. Kunkel (2003) looked for such a signal in precipitation data from Canada covering much of the last century but found "no discernible trend in the frequency of the most extreme [precipitation] events in Canada."

Conclusions

Rainfall records from Canada and Mexico provide no support for the claim that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998). Neither a long-term trend nor a late twentieth century trend of increasing precipitation is apparent in most records, which are instead dominated mainly decadal variability.

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6.1.2. Monsoons

Monsoonal climates bring abundant seasonal rainfall in Asia, northern Australia, South America, and South Africa. The Asian monsoon alone is said to influence nearly half of the world's population, people whose agriculture, way of life, and society all depend on the regularity of the summer monsoon.

A particularly useful perspective on monsoonal variation in climatic context is provided by Vuille *et al.*'s (2012) study of the South American monsoon, which builds on earlier research by Bird *et al.* (2011). These authors use proxy records derived from speleothems, ice cores, and lake sediments from the tropical Andes and Southeast Brazil to reconstruct a history of the monsoon system over the past two thousand years. They report very coherent monsoonal behavior over the past two millennia, in which decadal to multidecadal variability is superimposed on large climatic excursions that occurred during the Medieval Warm Period, Little Ice Age, and late twentieth century warm period. Monsoonal strengthening occurred during the LIA and weakening during the two warm periods. Vuille *et al.* conclude the longer scale climate anomalies "were at least partially driven by temperature changes in the Northern Hemisphere and in particular over the North Atlantic, leading to a latitudinal displacement of the Intertropical Convergence Zone and a change in monsoon intensity (amount of rainfall upstream over the Amazon Basin)."

Li *et al.* (2012) also provide context for changes in monsoonal activity, developing a summer surface salinity reconstruction for the past millennium from the Southern Okinawa Trough, East China Sea, based on a high-resolution diatom record. They found high-salinity conditions generally prevailed during the Medieval Warm Period (905–1450 AD), whereas the Little Ice Age was characterized by relatively low-salinity conditions, perhaps caused by increased freshwater discharge from Taiwan's Lanyang River.

The East Asian monsoon is a highly active and important part of the global climate system, with heavy summer monsoonal precipitation causing large discharges of freshwater into the southeastern East China Sea, variability in which has been documented from speleothem records (Wang *et al.*, 2001, 2008;

Partin *et al.*, 2007; Chang *et al.*, 2009). The report by Li *et al.* of increased China Sea region monsoonal activity during the Medieval Warm Period, and its reduction during the Little Ice Age, based on marine salinity variations, is an important confirmation of earlier land-based studies.

Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models, each with distinct physics and resolution, to simulate characteristics of the modern South American Monsoon System (SAMS). Model outputs were compared with data for the onset, end, and total rainfall of SAMS, as characterized by precipitation data for the period 1979–2006 derived from the Global Precipitation Climatology Project.

Bombardi and Carvalho found the annual precipitation cycle for SAMS “is poorly represented by most models”; for example, “poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models.” Most models, they note, “tend to underestimate precipitation during the peak of the rainy season.” The authors attribute the failure of the modeling to “the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle,” noting also, “simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon.”

In a similar study, Zhang *et al.* (2012) assessed the efficacy of GCM models to project variability and changes in the Asian monsoon. They used daily precipitable water and 850 hPa monsoon wind data to analyze potential changes in Asian monsoon onset, retreat, and duration, as simulated by 13 IPCC AR4 models. They report no model stands out as better than the 12 others and some models show “significant biases in mean onset/retreat dates and some failed to produce the broad features of how [the] monsoon evolves.” Flagrant contradictions occur between different groups of models. Over Asian land, for example, the 13 models “are nearly equally divided about the sign of potential changes of onset/retreat.” Zhang *et al.* concede they “do not know why the models are different in simulating these dominant processes and why in some models the ENSO influence is more significant than others.” They acknowledge also, as already found by Solomon *et al.* (2007) and Wang *et al.* (2009), that it is “unclear what are the key parameterizations leading to the differences in simulating ENSO and its responses to global warming.” In an important but little-cited statement, Zhang *et al.* conclude “there is a long way ahead before we can make skillful and reliable prediction of monsoon onset, duration, intensity and evolution in [a] warmed climate.”

Kim *et al.* (2012) studied the Asian monsoon using retrospective predictions (1982–2009) from the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) seasonal prediction systems. Both the SYS4 and CFSv2 models exhibited a cold bias in sea-surface temperature (SST) compared with observations over the Equatorial Pacific, North Atlantic, Indian Oceans, and a broad region in the Southern Hemisphere and a warm bias over the northern part of the North Pacific and North Atlantic Oceans. Additionally, the models predict excessive precipitation along the Intertropical Convergence Zone, equatorial Atlantic, equatorial Indian Ocean, and the maritime continent. The researchers found the southwest monsoon flow and Somali Jet are stronger in SYS4, while the southeasterly trade winds over the tropical Indian Ocean, the Somali Jet, and the Subtropical northwestern Pacific high are weaker in CFSv2 relative to the reanalysis.

Wang *et al.* (2013) investigated the decadal variability of the Northern Hemisphere summer monsoon. They found the variability observed since the 1970s was associated with an intensification of Hadley and Walker circulation, contradicting theoretical predictions and numerical model projections. They propose an alternative index, the mega-El Niño/Southern Oscillation, which combined with the AMO provides a good predictor of monsoon intensity. Their analysis shows the importance of internal feedback processes and displays a poor correspondence with global warming, although Wang *et al.* suggest it is consistent with projections of a warm Northern Hemisphere-cold Southern Hemisphere due to greenhouse gas forcing, due to an increased thermal gradient between the hemispheres based on the ERA-40 and ERAI reanalysis datasets.

Conclusions

The reports by Vuill *et al.* (2012) and Li *et al.* (2012) show both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period. Moreover, Bombardi and Carvalho (2009), Zhang *et al.* (2012), and Kim *et al.* (2012) unanimously conclude the predictive skill of monsoon models is inadequate. If the climate modeling enterprise cannot simulate the monsoonal precipitation that affects almost half the world’s population, climate GCMs cannot be anywhere near good enough to be relied on as a basis for setting policy.

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Earlier Research

Many other important papers have been published on the topic of the monsoon from the Middle East and across central Asia to Japan, including these:

- Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods for this record revealed "variations over the recent period of instrumental data are not unusual relative to the prior record." Though more frequent extended wet periods have occurred in recent decades, this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models," they write. Spectral analysis of the data reveals significant periodicities around 12 and 20–24 years, possibly "evidence for solar influences in these reconstructions for northeastern Mongolia."
- Neff *et al.* (2001) considered a ^{14}C growth-ring record and a $\delta^{18}O$ proxy record of monsoon rainfall intensity from an early Holocene (9,600–6,100 yBP) speleothem from northern Oman. Correlation between the two datasets was "extremely strong" and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the $\delta^{18}O$ record, and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Because variations in ^{14}C are generally attributed to variations in solar activity and the ^{14}C record correlated strong with the $\delta^{18}O$ record, and because their spectral analyses supported that correlation, Neff *et al.* conclude there is "solid evidence" that both signals stem from solar forcing.
- Kripalani *et al.* (2003) set out to test IPCC predictions of increased variability and strength of the

Asian monsoon under a global warming regime. The authors examined Indian monsoon rainfall for 1871–2001 using data obtained from 306 stations distributed across the country. The rainfall records display distinctive, three decade-long, alternating epochs of above- and below-normal rainfall but "no clear evidence to suggest that [either] the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming."

- Similar conclusions have been reached by several other authors. For example, "Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances over the Bay of Bengal and the Arabian Sea using 100-year (1890–1999) data and found significant decreasing trends." Kripalani *et al.* find "no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by [the] greenhouse warming scenario in model simulations." They conclude "the analysis of observed data for the 131-year period (1871–2001) suggests no clear role of global warming in the variability of monsoon rainfall over India," much as Kripalani and Kulkarni (2001) had concluded two years earlier.
- Kanae *et al.* (2004) examined the number and intensity of heavy precipitation events by comparing a climate-model-derived hypothesis with digitalized hourly precipitation data recorded at the Tokyo Observatory of the Japan Meteorological Agency for 1890–1999. The authors report many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s, making the 1990s seem to be unprecedented, but they note "hourly heavy precipitation around the 1940s is even stronger/more frequent than in the 1990s." Their plots of maximum hourly precipitation and the number of extreme hourly precipitation events both rise fairly regularly from the 1890s to peak in the 1940s, after which declines set in that bottom out in the 1970s. The trend then reverses again, to rise to endpoints in the 1990s that are not yet as high as the peaks of the 1940s.
- Touchan *et al.* (2003) developed two reconstructions of spring (May–June) precipitation for southwestern Turkey from tree-ring width measurements for the periods 1776–1998 and 1339–1998. The reconstructions show clear evidence of multiyear to decadal variations in spring precipitation, but both dry and wet periods of 1–2 years were well distributed throughout the records. With respect to more extreme events, the period that preceded the Industrial Revolution stood out, for "all of the wettest 5-year periods occurred prior to 1756" while the longest period of reconstructed spring drought was the four-year period 1476–1479, and the single driest spring was 1746. Turkey's greatest precipitation extremes occurred well before the late twentieth century warm period.
- In a modeling study, Kim *et al.* (2012) assessed the seasonal predictive skill for the Asian monsoon for 1982–2009 by comparing retrodictions of the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) models with actual temperature and rainfall records. The models were found to perform poorly, exhibiting both regional warm (North Pacific and North Atlantic) and cold (Southern Hemisphere) temperature biases; excessive precipitation along the Intertropical Convergence Zone; and both stronger (SYS4 model) and weaker (CFSv2 model) projections of monsoon trade winds.

Conclusions

The evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. In some cases the data suggest the opposite, and overall they provide support for the proposition that precipitation responds mostly to cyclical variations in solar activity.

The results of Kim *et al.* (2012) demonstrate there is a long way to go before GCM models can be viewed as reliable monsoon management aids. In addition, the results of Wang *et al.* (2013) suggest a better understanding of the role of internal feedback processes as captured by the ENSO, PDO, AMO, and other indices would provide a better approach to forecasting monsoon behavior than focusing solely on external forcings.

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6.1.3. Snowfall, Avalanches

On March 20, 2000, a British newspaper reported "Snowfalls are just a thing of the past" based on statements by a member of the Climatic Research Unit of the University of East Anglia, who claimed within a few years snowfall will become "a very rare and exciting event" and "children just aren't going to know what snow is." The U.K.'s Hadley Centre for Climate Prediction and Research said eventually British children would have only a "virtual" experience of snow via movies and the Internet.

A model developed at the U.S. National Oceanic and Atmospheric Administration (NOAA) published in the *Journal of Climate* projected the majority of the planet would experience less snowfall as a result of global warming due to increasing atmospheric CO_2. The predicted decline in snowfall was expected to cause serious problems for ski resorts and areas in the western United States that rely on snowmelt as a source of fresh water. Oregon and Washington would get less than half their usual amount of snow.

In June 2013, more than 100 ski resorts, concerned global warming would reduce snowfall and curtail skiing, joined the Business for Innovative Climate and Energy Policy Climate Declaration urging Americans to "use less electricity," "drive a more efficient car," and choose "clean energy" to combat climate change and save their ski resorts. The 2007 report of the IPCC warns of a difficult future for the industry: "…snow cover area is projected to contract[,] … mountainous areas will face glacier retreat, reduced snow cover and winter tourism[, and] … shifting of ski slopes to higher altitudes."

And yet, three of the top five snowiest winters in the Northern Hemisphere on record have occurred in the past five years (Figure 6.1.3.1).

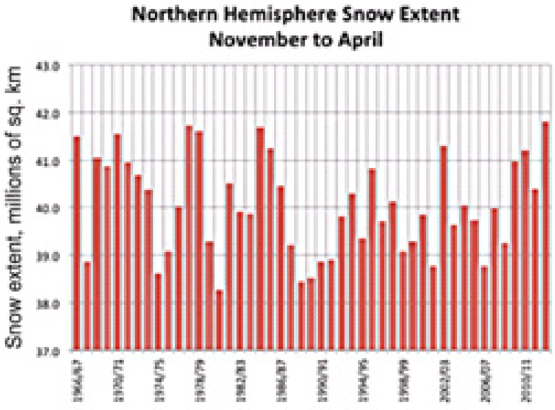

Figure 6.1.3.1. Annual winter snow extent in the Northern Hemisphere, November to April, 1966–2013 (Rutgers University, Global Snow Lab).

In related research, Eckert *et al.* (2010) examined the hypothesis that global warming might cause a dangerous increase in numbers of snow avalanches in the French Alps. Because avalanches are mainly governed by temperature fluctuations in combination with heavy snow and strong wind regimes, both Eckert *et al.* and the IPCC have deemed it likely they will be strongly influenced by climatic fluctuations. Eckert *et al.* analyzed snow avalanches using data from the *Enquete Permanente sur les Avalanches*—EPA, a chronicle that describes avalanche events on approximately 5,000 determined paths in the French Alps and the Pyrenees.

Eckert *et al.* found no strong changes in mean avalanche activity or in the number of winters of low or high activity over the last 60 years of record. Similar results have been reported from the Swiss Alps for the second half of the twentieth century by Laternser and Schneebeli (2002) and by other researchers, including Schneebeli *et al.* (1997) and Bader and Kunz (2000), who report no change in extreme snowfalls and catastrophic avalanches around

Davos, Switzerland during the twentieth century. Jomelli *et al.* (2007) found "no correlation between the fluctuations in avalanche activity between 1978 and 2003 and large-scale atmospheric patterns" in the Maurienne Valley in France, and Jomelli and Pech (2004) suggest avalanche magnitude at low altitudes has declined since 1650 in the Massif des Ecrins in the French Alps.

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Earlier Research

Other recent studies of the relationship between global warming and snow or avalanche activity include the following:

- Kunkel *et al.* (2009a and 2009b) used 440 long-term, homogeneous snowfall records to examine "temporal variability in the occurrence of the most extreme snowfall years, both those with abundant snowfall amounts and those lacking snowfall," defined as the highest and lowest tenth percentile winter snow amounts. Their data came from the conterminous United States over the 107-year period from 1900–1901 to 2006–2007.

Kunkel *et al.* (2009b) found large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States, balanced by large increases in the frequency of low-extreme snowfall years in the northeast, southeast, and northwest. The scientists determined overall "the area-weighted conterminous United States results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-year period."

- Kilpelainen *et al.* (2010) report on the degree to which Finnish forests are damaged by snow load on their branches, claiming across Europe such loading "has accounted for a mean annual amount of almost one million cubic meters of damaged wood in managed forests over the period 1950–2000." Damage results primarily from stem breakage or bending when the soil is frozen, although trees also can be uprooted if the soil is not frozen, and damage by insects or fungal attacks are common in trees suffering from snow damage.

To calculate risk of snow-induced damage, Kilpelainen *et al.* employed a snow accumulation model in which cumulative precipitation, air temperature, and wind speed were derived from the A2 scenario of the FINADAPT project (Ruosteenoja *et al.*, 2005), where the air's CO_2 concentration was estimated to rise to 840 ppm by 2100 and mean air temperatures were projected to increase by almost 4°C in summer and more than 6°C in winter. The model was tested and trained using real-world data obtained by the Finnish Meteorological Institute (Venalainen *et al.*, 2005) for the 30-year baseline period of 1961–1990.

Defining the risk of snow-induced forest damage as proportional to the number of days per year when the accumulated amount of snow exceeds 20 kg m-2, the six scientists calculated the mean annual number of risk days in Finland declined by 11 percent, 23 percent, and 56 percent relative to the 1961–1990 baseline period for the first, second, and third 30-day simulation periods they modeled (1991–2020, 2021–2050, and 2070–2099), respectively. For the most hazardous areas of northwest and northeast Finland they also report "the number of risk days decreased from the baseline period of over 30 days to about 8 days per year at the end of the century."

- Peng *et al.* (2010) used snow-depth measurements collected at 279 meteorological stations in northern China, plus colocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate changes in snow depth for 1980–2006 and to analyze the effects of those changes on vegetative growth during the following spring and summer. Peng *et al.* report winter snow depth overall increased in northern China over the past 30 years, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed. Here, positive correlations exist between mean winter snow depth and spring NDVI data. In addition, they note Piao *et al.* (2005) had determined the net primary productivity of the same desert and grasslands during 1982–1999 "increased by 1.6% per year and 1.1% per year, respectively" and "desertification has been reversed in some areas of western China since the 1980s," as reported by Runnstrom (2000), Wu (2001), Zhang *et al.* (2003), and Piao *et al.* (2005). Peng *et al.* conclude the "increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms." They further note the frequency of sand-dust storms has "declined in China since the early 1980s (Qian *et al.*, 2002; Zhao *et al.*, 2004)."

- Teich *et al.* (2012) analyzed 21 snow and weather variables associated with 189 winter forest avalanches in the Swiss Alps between 1985 and 2006, an acknowledged human hazard (Bebi *et al.*, 2009; Martin *et al.*, 2001). The avalanches were spread geographically throughout the Alps and at heights ranging from 700 to 2,200 m height. The researchers found the number of potential forest avalanche days decreased at 11 of 14 snow and weather stations [79 percent] for new snow forest avalanches and at 12 of 14 stations [86 percent] for old snow forest avalanches, independent of elevation and climatic region. They conclude such "negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under current climate change." Thus, noting the currently observed increase in forest cover density in the Swiss Alps (Bebi *et al.*, 2001; Brandi, 2010; Krumm *et al.*, 2011), "it is likely that avalanche releases in forested terrain will become less frequent in the future."

Conclusions

The cited studies indicate a warming generally does not affect the frequency of avalanches. For instance, and after a comprehensive review of the work of other scientists, Eckert *et al.* (2010) conclude "climate change has recently had little impact on the avalanching rhythm in this region [the French Alps]." Regarding forest damage, the decline in the number of risk days reported from northern Finland by Kilpelainen *et al.* (2010) represents a warming-induced *decrease* in risk of snow damage to forests on the order of 75 percent.

Peng *et al.*'s (2010) studies show as the world has warmed over the past three decades, China above 40°N latitude has seen an increase in winter snow depth that has promoted increased vegetative growth in desert areas and grasslands and resulted in a reduction in sand-dust storms. These climate-related changes are obviously positive developments.

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6.1.4. Evaporation

Evaporation is the primary source of atmospheric water vapor, a powerful greenhouse gas, and so is of particular interest to climate scientists. Huntington (2006) notes direct measurements of evaporation (pan evaporation) show a reduction in evaporation over the twentieth century, whereas indirect estimates suggest an increase.

Roderick and Farquhar (2002) linked a reduction in pan evaporation rates to a reduction in insolation (solar dimming) at ground level due to increasing cloud cover and atmospheric aerosols. Subsequently Roderick *et al.* (2009a) calculated a reduction of 4.8 W/m^2 for Australia as driving the observed reduction in pan evaporation. The Australian results are extended to the global behavior by Roderick *et al.* (2009b), where a global reduction in pan evaporation is attributed to a combination of wind stilling and solar dimming. The authors also observe the interpretation of pan evaporation depends on whether the observations are from water-limited or energy-limited sites. For energy-limited sites, the evaporation occurs at the maximum rate possible for the radiative flux present, and declining pan evaporation also indicates declining evapo-transpiration. For water-limited sites, evaporation is restricted by the available water, and evapo-transpiration depends on the supply of precipitation. Therefore, Roderick *et al.* argue evapo-transpiration can rise while pan evaporation decreases, if the supply of precipitation increases sufficiently. This implies dry areas are getting wetter.

Recognizing the importance of near-surface wind speed for evaporation, McVicar *et al.* (2010) noted the "occurrence of widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years," citing papers by Roderick *et al.* (2007), McVicar *et al.* (2007; 2008), Pryor *et al.* (2009), and Jiang *et al.* (2010). Such a change, now widely termed "stilling," will be a key factor in reducing the atmospheric demand that drives actual evapotranspiration when water availability is not limited, as in the case of lakes and rivers.

In addition, McVicar *et al.* note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases (as demonstrated by McVicar *et al.*, 2007). Increasing wind speeds, they point out, lead to increases in atmospheric evaporative demand, and decreasing wind speeds do the opposite. These changes are significant for people who depend on water resources derived from mountainous headwater catchments: More than half the world's population lives in catchments with rivers originating in mountainous regions (Beniston, 2005), and this water supports about 25 percent of the global gross domestic product (Barnett *et al.*, 2005).

Defining u_z as change in wind speed with change in elevation—that is, $u_z = \Delta u/\Delta z$, where $\Delta u = u_2 - u_1$, $\Delta z = z_2 - z_1$, and $z_2 > z_1$—McVicar *et al.* calculated monthly averages of u_z, using 1960–2010 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. They suggest their research constitutes "the first time that long-term trends in u_z

in mountainous regions have been calculated," and their u_z trend results show u to have declined more rapidly at higher than at lower elevations in both study areas.

The double benefit of 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, thus providing more water for people who obtain it from those sources. As McVicar *et al.* note, the "reductions in wind speed will serve to reduce rates of actual evapo-transpiration partially compensating for increases in actual evapo-transpiration due to increasing air temperatures."

Some papers in the literature (e.g., Cai *et al.*, 2009), and also the published IPCC fourth and draft fifth *Assessment Reports*, confuse the causal physics of the relationship between temperature and evapotranspiration by assuming increasing temperature causes drought. In reality, when incoming radiation falls on a moist surface this energy is partitioned into evapotranspiration (latent heat) and heating of the near surface/atmosphere (sensible heat). During drought, where moisture is limited, less of the incoming energy can be used for latent heat (i.e., reduced evapotranspiration) and consequently more sensible heat occurs. The consequence is that air temperatures rise as evapotranspiration is reduced (Lockart *et al.*, 2009a, b).

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6.1.5. Drought

Even a moderate drought can have devastating effects on regional agriculture, water resources, and the environment. Many climate scientists and agriculturists have expressed growing concern about worldwide drying of land areas and increasing evapotranspiration, which they attribute to man-induced global warming. Some recent peer-reviewed studies suggest the severity and length of droughts is increasing over various regions due to global warming (e.g., Briffa *et al.*, 2009; Cai *et al.*, 2009). But in the United States, droughts have become shorter, less frequent, less severe, and less widespread over the past century, peaking during the Dust Bowl era of the 1930s, as clearly evidenced by the heat wave index for the period 1895–2008 (Figure 6.1.5.1).

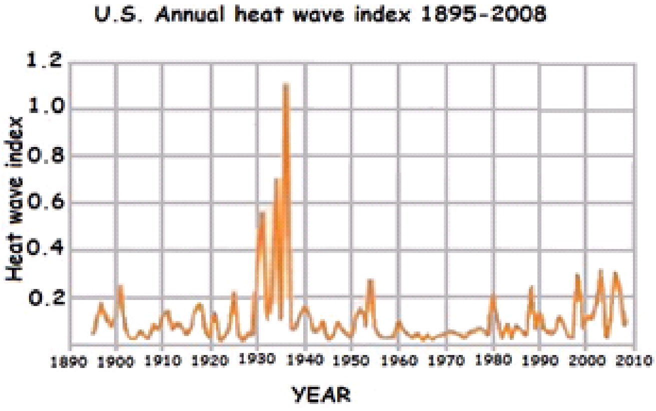

Figure 6.1.5.1. Heat Wave Index for USA, 1895–2008 (NOAA CCSP U.S. Climate Change Science Program, 2009).

Drought represents moisture deficit and therefore is an end-member of the precipitation spectrum. Many of the papers discussed earlier have referred to the issue. We include here several other important papers for which drought is the primary focus.

- Providing a long-term perspective of the climate cycle that stretches from the Medieval Warm Period to the late twentieth century warming, Laird *et al.* (2012) developed diatom-based proxy records for sediment cores from six lakes that provide a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada. The study was intended to address concerns that droughts similar to, or more extreme than, the 1930s Dust Bowl drought are a likely outcome of human-forced global warming and could perhaps last for several decades to centuries (Seager *et al.*, 2007; Cook *et al.*, 2010; Romm, 2011). A consequence of such droughts is decreased lake levels and river flows (Schindler and Lee, 2010).

Laird *et al.* reported a synchronous change had occurred across all of the six lakes, indicating "a period of prolonged aridity" during the Medieval Warm Period (c. 900–1400 AD). The general coincidence in time of this event at the six sites suggests an extrinsic climate forcing (Williams *et al.*, 2011) of natural origin. A parallel study by Schmieder *et al.* (2011) of five topographically closed lakes in Nebraska "indicated relative (climate) coherency over the last 4000 years, particularly during the MCA [Medieval Climate Anomaly] with all lakes indicating lake-level decline." Schmieder *et al.* also report "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 AD in Elk Lake (Dean, 1997) and δ^{18}O from calcite indicated an arid period from ~1100 to 1400 AD in Steel Lake (Tian *et al.*, 2006)." They note, "in Manitoba, the cellulose δ^{18}O record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 AD, and a less-severe dry period from 1320 to 1340 AD (Buhay *et al.*, 2009)" and relatively warm conditions during the Medieval Warm Period "have been inferred from pollen records in the central boreal region of Canada and in Wisconsin" (Viau and Gajewski, 2009; Viau *et al.*, 2012; Wahl *et al.*, 2012)."

- In a study of drought in the global context over the past 60 years, Sheffield *et al.* (2012) utilize datasets on temperature, precipitation, and surface energy parameters (wind, specific humidity, etc.) to calculate the standard Palmer Drought Severity Index (PDSI) using two different equations. The PDSI-TH (Thornwaite formulation of evapotranspiration) and PDSI-PM (Penman-Montheith formulation) differ in that the TH model estimates evapotranspiration on the basis of air temperature (a proxy for potential evapotranspiration, not because of causal physics), whereas PM offers a more physically based evapotranspiration formulation, where temperature is utilized only to calculate near surface atmosphere humidity deficit. The TH model implicitly assumes no trend in air temperatures over the long term. The PDSI-TH approach overestimates evapotranspiration as long-term trends in temperature are apparent. The PDSI-PM equation does not respond to the temperature trend, as temperature is only an indirect variable.

Both the older, conventional index (PDSI-TH) and the newer index (PDSI-PM) show an increase in drought over recent years, though the trend for the latter was not statistically significant. The regions of decreasing trends in potential evaporation are in general agreement with areas of global dimming, decreasing wind speed, and changes in other surface parameters but not temperature. These results suggest previous calculations of global drought have been overestimated, and the authors conclude their study has implications for understanding changes in the terrestrial hydrological cycle and the future impacts of global warming on agriculture and water resources. Sheffield *et al.* (2009) arrived at similar conclusions.

Conclusions

The relationship between the occurrence of drought and global warming is, at best, weak. Nonetheless, in some places, such as North America, severe droughts occurred during the Medieval Warm Period. Given the absence of similar droughts during the warming in the late twentieth century, two conclusions follow. First, the Medieval Warm Period must have been more extreme in terms of both high temperature and its duration than anything experienced recently. Second, the occurrence of such extra warming is strong evidence that warmings greater than the recent one 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. This research thus suggests both recent warming and drought are the result of something other than anthropogenic CO_2 emissions.

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6.1.6. Rivers and Streamflow

Model projections suggest CO_2-induced global warming may induce large changes in global streamflow characteristics, which has led many authors and the IPCC to claim warming will lead to the intensification of the hydrological cycle and the occurrence of more floods (Labat, 2004; Huntington, 2006; Gerten *et al.*, 2008; Dai *et al.*, 2009).

Accordingly, many scientists have examined streamflow, or proxy streamflow, records in an effort to elucidate these claimed relationships. On the assumption that global runoff represents an integrated response to continental hydrological dynamics, some authors invert the reasoning and use changes in hydrology as an indicator of global warming (Gleick, 2003; Nilsson *et al.*, 2005; Milliman *et al.*, 2008). These matters relate to forecasts of precipitation variability, floods, and droughts, issues also addressed elsewhere in this chapter.

In a pivotal study of this relationship that formed part of the World Climate Program supported by UNESCO and the WMO, Kundewicz *et al.* (2004) analyzed long-term and high-quality data on streamflow to determine whether floods have increased worldwide, as predicted by climate models. They concluded, "the analysis of 195 long time series of annual maximum flows, stemming from the GRDC holdings does not support the hypothesis of general growth of flood flows. … Observations to date provide no conclusive and general proof as to how climate change affects flood behaviour. There is a discontinuity between some observations made so far. Increases in flood maxima are not evident whilst model-based projections show a clear increase in intense precipitation."

Milliman *et al.* (2008) examined discharge trends over the second half of the twentieth century for 137 rivers whose combined drainage basins represent about 55 percent of world land area. They found "between 1951 and 2000 cumulative discharge for the 137 rivers remained statistically unchanged," as did global on-land precipitation over the same period.

Munier *et al.* (2012) also estimated global runoff for the period 1993–2009, using two methods both of which were derived by coupling modeled land-atmosphere and ocean-atmosphere water budgets with independent datasets in order to estimate water storage variations in several water budget compartments. The datasets included atmospheric re-analyses, land surface models, satellite altimetry, and direct ocean temperature measurements. The results of both sets of calculations of global runoff correlate well for the full period 1993–2006. The researchers found "no significant trend … over the whole period" for either method of calculation. They conclude, "an intensification of the global water cycle due to global warming is not obvious over the last two decades."

Conclusions

The IPCC hypothesis regarding changes in streamflow should have been tested by these studies, but the hypothesis is so loosely formulated as to be essentially untestable. Predicting global warming will lead to more frequent and/or more intense flooding and drought, as the IPCC does, ensures predictive success for just about any dataset studied for any time and any place.

Nevertheless, none of the Kundzewicz *et al.* (2004), Milliman *et al.* (2008), or Munier *et al.* (2012) studies was able to identify any change in global runoff over the past 60 years. The simplest and most obvious conclusion to draw is that of Milliman *et al.* (2008), who report "neither discharge nor precipitation changed significantly over the last half of the 20th century, offering little support to a global intensification of the hydrological cycle."

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Earlier Research

Here we summarize other studies that address whether late twentieth century warming might have caused changes in streamflow regimes.

- Lins and Slack (1999) analyzed streamflow trends for 395 climate-sensitive stations, including data from more than 1,500 individual gauges, located throughout the United States, the longest datasets stretching back to 1914. They found many more flow up-trends than down-trends, with slight decreases occurring "only in parts of the Pacific Northwest and the Southeast." Their findings indicate "the conterminous U.S. is getting wetter, but less extreme."
- Brown *et al.* (1999) studied siliciclastic sediment grain size, planktonic foraminiferal and pteropod relative frequencies, and the carbon and oxygen isotopic compositions of two species of planktonic foraminifera in cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico to delineate the changing characteristics of the Mississippi River over the past 5,300 years. They identified the occurrence of large megafloods—which they describe as having been "almost certainly larger than historical floods in the Mississippi watershed"—at 4,700, 3,500, 3,000, 2,500, 2,000, 1,200, and 300 years before present. These flow events probably related to times of export of extremely moist Gulf air to midcontinental North America, driven by naturally occurring millennial and multidecadal oscillations in Gulf of Mexico ocean currents.
- Hidalgo *et al.* (2000) used principal components analysis to reconstruct streamflow in the Upper Colorado River Basin from tree-ring data, comparing their results with the streamflow reconstruction of Stockton and Jacoby (1976). Their work supported the earlier study but delivered a better understanding of periods of below-average stream-flow or regional drought. Hidalgo *et al.* identify "a near-centennial return period of extreme drought events in this region" that stretched back to the early 1500s, and their data suggest the existence of past droughts that surpassed the worst of the twentieth century.
- Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to develop annual precipitation and streamflow histories for the period 1651–1995. The research revealed variations over the recent period of instrumental data are not unusual relative to the prior record, as judged against the standard deviation and five-year intervals representative of extreme wet and dry periods. Although the reconstructions "appear to show more frequent extended wet periods in more recent decades," Pederson *et al.* conclude this observation does not provide "unequivocal evidence of an increase in precipitation as suggested by some climate models." Spectral analysis of the data also revealed significant periodicities of 12 and 20–24 years, hinting at the presence of a solar influence.
- Knox (2001) studied how conversion of the U.S. Upper Mississippi River Valley from prairie and forest to crop and pasture land in the early 1800s influenced subsequent watershed runoff and soil erosion rates. Initially, the conversion of the region's natural landscape to agricultural use increased surface erosion rates by three to eight times those characteristic of pre-settlement times. The land-use conversion also increased the peak discharges from high-frequency floods by 200 to 400 percent. Since the late 1930s, however, surface runoff has been decreasing. The decrease "is not associated with climatic causes," according to Knox, who reports an analysis of the variation in storm magnitude over the same period showed no statistically significant trend.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for the period 1948–1997 in a semiarid region of the southwestern United States, the Rio Puerco Basin of New Mexico. They reported "a statistically significant [annually] increasing trend in precipitation in the basin was detected." This trend was 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; monthly totals increased in low-flow months and decreased in high-flow months.
- Hisdal *et al.* (2001) analyzed more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and

frequency of drought over the following four time periods: 1962–1990, 1962–1995, 1930–1995, and 1911–1995. They concluded, "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." On the contrary, the trends pointing toward decreasing streamflow deficits or fewer droughts outnumbered trends of increasing streamflow deficits or more droughts.

- Cluis and Laberge (2001) checked for recent changes in runoff at 78 rivers "geographically distributed throughout the whole Asia-Pacific region," using streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany). Mean start and end dates of the river flow records were 1936 ± 5 years and 1988 ± 1 year. The researchers determined mean river discharges were unchanged in 67 percent of the cases investigated; where trends did exist, 69 percent were for lesser flows. Maximum river discharges were unchanged in 77 percent of the cases investigated, and where trends did exist 72 percent were again downward. Minimum river discharges were unchanged in 53 percent of cases investigated; where trends existed, 62 percent of them were upward.
- Campbell (2002) analyzed grain size in 4,000-year-long sediment cores from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of climate variability. The research identified periods of both increasing and decreasing grain size (a proxy for moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales. The predominant departures from the background norm included several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500–1900), the Medieval Warm Period (about AD 700–1300), the Dark Ages Cold Period (about BC 100 to AD 700), and the Roman Warm Period (about BC 900–100). A standardized median grain-size history revealed the highest rates of stream discharge during the past 4,000 years occurred during the Little Ice Age, approximately 300–350 years ago, when grain sizes were about 2.5 standard deviations above the 4,000-year mean. By contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean. Grain size over the past 150 years generally has remained above average, with no indication of a climatic trend related to twentieth century warming.
- McCabe and Wolock (2002) evaluated U.S. records for 1895–1999 for three hydrologic parameters: precipitation minus annual potential evapotranspiration, the surplus water that eventually becomes streamflow, and the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. This investigation revealed a statistically significant increase in the first two of these parameters, and for the third there was no change, indicating water has become more available within the conterminous United States and there has been no increase in the amount of water required for optimum plant growth.
- Pekarova *et al*. (2003) analyzed annual discharge rates of selected large rivers of the world for recurring cycles of wet and dry. For rivers with long enough records, they also derived long-term discharge rate trends. The authors could not identify "any significant trend change in long-term discharge series (1810–1990) in representative European rivers," including the Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone, and Po.
- McCabe and Clark (2005) used daily streamflow data representing snowmelt for 84 stations in the western United States, each with complete water-year information for the period 1950–2003. Each station's mean streamflow trend was determined for the past half century as well as any marked steps that may have occurred in each data series. As other researchers had reported previously, McCabe and Clark determined the timing of snowmelt runoff for many rivers in the western United States has shifted earlier, not as a trend but as a step change during the mid-1980s. This change occurred coincidentally with "a regional step increase in April-July temperatures during the mid-1980s." After discussing the possible reasons for these changes, McCabe and Clark conclude "the observed change in the timing of snow-melt runoff in the western United States is a regional response to natural climatic variability and may not be related to global trends in temperature."
- Carson and Munroe (2005) used tree-ring data collected by Stockton and Jacoby (1976) from the Uinta Mountains of Utah to reconstruct the mean annual discharge in the Ashley Creek watershed for the period 1637 to 1970. Significant persistent departures from the long-term mean occurred throughout the 334-year record of streamflow. The periods 1637–1691 and 1741–1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows, indicative of persistent drought or near-drought

conditions. By contrast, there was an overall abundance of extremely large flows and relatively few extremely small flows during the periods 1692–1740 and 1898–1945, indicative of wetter conditions.

- Rood *et al*. (2005) analyzed streamflow trends for rivers fed by relatively pristine watersheds in the central Rocky Mountain Region extending from Wyoming (United States) through British Columbia (Canada). Both parametric and nonparametric statistical analyses were used to assess nearly a century of annual discharge (ending about 2002) along 31 river reaches that drain this part of North America. They found river flows in the region declined over the past century by an average of 0.22% per year, with four of them exhibiting recent decline rates exceeding 0.5% per year. This finding "contrasts with the many current climate change predictions that [this] region will become warmer and wetter in the near-future."
- Déry and Wood (2005) analyzed hydrometric data for 1964–2003 from 64 northern Canadian rivers that drain more than half of the country's landmass. After assessing variability and trends in the data, they explored the influence of large-scale teleconnections on the data record. They identified a statistically significant mean decline of approximately 10 percent in the discharge rates of the 64 rivers over the four decades of their study, matching a decline in precipitation known for northern Canada between 1964 and 2000. Déry and Wood conclude the decline in river discharge was driven "primarily by precipitation rather than evapotranspiration." They also report statistically significant links between the declines in precipitation and streamflow and the Arctic Oscillation, the El Niño/Southern Oscillation, and the Pacific Decadal Oscillation. No influence was discerned from twentieth century warming per se.
- Cao *et al.* (2006) conducted a streamflow study for the Qinghai-Tibet Plateau to evaluate theoretical arguments and models that suggest deleterious human-caused changes in streamflow might occur there (Houghton *et al.*, 2001; Rahmstorf and Ganopolski, 1999; Bruce *et al.*, 2002). The modeled scenarios suggest global warming should cause a precipitation increase in northwest China, with one researcher predicting a regional climatic shift from warm-dry to warm-wet (Shi, 2003) accompanied by an increase in total river discharge.

  Cao *et al*. analyzed annual discharge data for five large rivers of the Qinghai-Tibet Plateau over the period 1956–2000, using the Mann-Kendall nonparametric trend test. They determined "river discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the Northern Hemisphere surface air temperature," and therefore with late twentieth century warming.
- Woodhouse *et al*. (2006) generated updated proxy reconstructions of streamflow for four key gauges in the Upper Colorado River Basin (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona). They determined 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 also report "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." They conclude their "analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate" and "droughts more severe than any 20th to 21st century event [have] occurred in the past."
- Novotny and Stefan (2006) analyzed Nevada (USA) streamflow records prior to 2002 from 36 gauging stations in five major river basins, with lengths ranging from 53 to 101 years. They derived seven annual streamflow statistics: mean annual flow, seven-day low flow in winter, seven-day low flow in summer, peak flow due to snowmelt runoff, peak flow due to rainfall, and high and extreme flow days. Significant trends occurred for each of the seven statistics somewhere in the state, but in most cases the trends are not monotonic but periodic. Not surprisingly, "the mean annual stream flow changes are well correlated with total annual precipitation changes."

  With respect to extreme hydrological events, Novotny and Stefan found peak flood flows due to snowmelt runoff "are not changing at a significant rate throughout the state," but seven-day low flows or base flows are "increasing in the Red River of the North, Minnesota River and Mississippi River basins during both the summer and winter" and the "low flows are changing at a significant rate in a significant number of stations and at the highest rates in the past 20 years." They note "this finding matches results of other studies which found low flows increasing in the upper Midwest region including Minnesota (Lins and Slack, 1999; Douglas *et al*., 2000)."

  The changes Novotny and Stefan described are mostly beneficial, because "water quality and aquatic ecosystems should benefit from increases in low flows in both the summer and winter, since water quality stresses are usually largest during low flow periods." In addition, they note, "other good news is that spring floods (from snowmelt), the largest floods in Minnesota, have not been increasing significantly."

- Woodhouse and Lukas (2006) developed a network of 14 annual streamflow reconstructions, 300 to 600 years long, for the Upper Colorado and South Platte River basins, Colorado, based on tree-ring chronologies. The authors conclude "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries"; and further, "paleoclimatic studies indicate that the natural variability in 20th century [streamflow] gage records is likely only a subset of the full range of natural variability," as discovered also by Stockton and Jacoby (1976), Smith and Stockton (1981), Meko *et al.* (2001), and Woodhouse (2001). They conclude "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."
- Davi *et al.* (2006) used tree-ring-width chronologies from five sampling sites in west-central Mongolia to develop precipitation models. The longest of the five tree-ring records (1340–2002) was used to reconstruct a proxy streamflow record for 1637–1997. Davi *et al.* report there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation [1937–2003]." Their streamflow history indicates "the wettest 5-year period was 1764–68 and the driest period was 1854–58," while "the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83."
- MacDonald *et al.* (2007) used tree-ring records from northern Eurasia to provide reconstructions back to AD 1800 of annual discharge for the major rivers that enter the Arctic Ocean: S. Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma. Annual discharges in the mid to late twentieth century were not significantly greater than discharges experienced over the preceding 200 years and "are thus still within the range of long-term natural variability." MacDonald *et al.* also found "longer-term discharge records do not indicate a consistent positive significant correlation between discharge [and] Siberian temperature," but instead a weak *negative* correlation over the period of their study.
- St. George (2007) used streamflow data from the Winnipeg River watershed to assess Burn's (1994) suggestion that a doubling of the air's CO_2 content might increase the severity and frequency of droughts in the prairie provinces of Canada (Alberta, Saskatchewan, Manitoba), an assertion that conflicts with climate modeling suggesting runoff in Manitoba instead could increase 20 to 30 percent by 2050 (Milly *et al.*, 2005). St. George assembled streamflow data from nine gauge stations for the period 1924–2003 from the Water Survey of Canada's HYDAT data archive, with precipitation and temperature data taken from Environment Canada's Adjusted Historical Canadian Climate Data archive.

  St. George's analysis showed "mean annual flows have increased by 58% since 1924 ... with winter streamflow going up by 60–110%," primarily because of "increases in precipitation during summer and autumn." A link to climate is suggested by the fact that similar "changes in annual and winter streamflow are observed in records from both regulated and unregulated portions of the watershed." However, other studies have reported declining flow for many rivers in the Canadian prairies (Westmacott and Burn, 1997; Yulianti and Burn, 1998; Déry and Wood, 2005; Rood *et al.*, 2005). In essence, conflicting conclusions have been reached about the hydrology of the prairie provinces of Canada, especially in Manitoba, making it impossible to issue confident forecasts about future streamflows. Nonetheless, St. George asserts "the potential threats to water supply faced by the Canadian Prairie Provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin."
- Smith *et al.* (2007) presented an analysis of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia, with a focus on assessing low-flow trends since the 1930s. They conclude "a clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or 'low flows,' have risen in northern Eurasia during the 20th century" with the greatest minimum flow increases since ~1985.
- Mauas *et al.* (2008) studied Parana River, South America, streamflow data since 1904, when the daily record began. The river is the world's fifth-largest in terms of drainage area and fourth-largest with respect to streamflow. The researchers found "the flow of the Parana is larger in the last three decades, with a mean value almost 20% larger than that of the first 70 years of the twentieth century." They note "the stream flow during the last 30 years has increased in the months in which the flow is minimum, while the flow remains more or less constant during the months of maximum

... [and] … the same trend is also found in other rivers of the region."

Mauas *et al.* also report a strong correlation between solar parameters and periodicities present in the detrended time series of streamflow data. Both sunspot number and total solar irradiance correlate at a significance level greater than 99.99% with Pearson's correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69 respectively.

- Hannaford and Marsh (2008) utilized a U.K. benchmark network of 87 near-natural catchments (as identified by Bradford and Marsh, 2003) to appraise trends in high-flow regimes in catchments unaffected by human disturbances. They write, "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments, and projections suggest that flooding may increase in [the] future as a result of human-induced warming."

The two researchers 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," with similar changes being absent from lowland areas in the south and east of the U.K. The high-flow indicators they observed in the northwest are correlated with the North Atlantic Oscillation (NAO), suggesting the recent upward trend in high-flow events may reflect one part of a multidecadal cycle.

- Lloyd (2010) studied flow trends in the Breede River, the largest in South Africa's Western Province and economically significant. Prior modeling studies had predicted flows into the river could be reduced dramatically by a warming climate (e.g., Steynor *et al.*, 2009). Steynor *et al.* analyzed flow data for five sites in the Breede Valley to compute historical flow-rate trends over historic periods of warming ranging from 29 to 43 years in length. All the calculated future flow rates exhibited significant negative change, averaging -25% for one global climate model and -50% for another. The mean past trend of four of the five Breede River stations also was negative (-13%), with the remaining station indicating an increase of +14.6%. Lloyd noted "changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows" of the negative-trend stations.

Because Steynor *et al.* had presumed warming would lead to decreased flow, they assumed their projections were correct. Lloyd was able to demonstrate those results were driven primarily by unaccounted-for land use changes in the five catchments; the one site that had "a pristine watershed" was the one with the "14% increase in flow over the study period." Lloyd concluded his results were contrary to the climate change predictions and indicate "climate change models cannot yet account for local climate change effects."

- Panin and Nefedov (2010) provided a riverine geomorphological and archaeological study of the Upper Volga and Zapadnaya Dvina Rivers (Russia) to assess the hypothesis that human settlement on floodplains is controlled by the frequency of seasonal floods. Their database comprised occupational layers for 1,224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province.

Panin and Nefedov identified 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 associated with periods of warming and cooling, respectively. The period AD 1000–1300 Middle Ages provided particularly favorable conditions for floodplain settlement in areas subject to inundation today. Panin and Nefedov conclude this interval "can be regarded as hydrological analogues of the situation of the late 20th–early current century." This relationship 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.

- Zhang *et al.* (2010) analyzed twentieth century daily streamflow for eight unregulated streams in the Susquehanna River Basin, USA. This basin includes parts of the states of Maryland, New York, and Pennsylvania and is the largest freshwater contributor to Chesapeake Bay, comprising 43 percent of the bay's drainage area and providing 50 percent of its water. The records studied start at slightly different times, but all end in 2006 with record-lengths ranging from 68 to 93 years and an average length of 82.5 years. The data were subjected to monotonic trend tests, each of which used different beginning and ending times, to detect changes and trends in annual minimum, median, and maximum daily streamflow.

Zhang *et al.* found annual maximum streamflow "does not show significant long-term change," but there was "a considerable increase in annual minimum flow for most of the examined watersheds, and a noticeable increase in annual median flow for about half of the examined watersheds."

- Hannaford and Buys (2012) analyzed trends in U.K. river flow between 1969 and 2008 in a network of 89 near-natural catchments in an attempt to distinguish natural climate-driven trends from direct anthropogenic disturbances. Previous model studies have suggested the U.K. will experience wetter winters and hotter, drier summers in the future, causing decreasing river flow in summer and increases in winter (Murphy *et al.* 2009; Arnell, 2011; Prudhomme *et al.*, 2012), with increases in flood frequency and magnitude in some regions (Arnell, 2011; Kay and Jones, 2012; Bell *et al.*, 2012). Real-world data, however, indicate droughts in 2004–2006 (Marsh *et al.*, 2007) and 2010–2012 (Marsh, 2012) were caused by successive dry winters, while a sequence of wet summers occurred in the 2007–2012 period (e.g., Marsh and Hannaford, 2008).

  In apparent harmony with climate model projections, Hannaford and Buys observed "an overall increase in winter river flows." But in conflict with what the models predict, they report "in summer, there is no compelling evidence for a decrease in overall runoff or low flows, which is contrary to trajectories of most future projections." More specifically, they found the predominance of increasing flow trends across the seasons, coupled with limited decreases in low flows, is favorable from a water management perspective; the lack of any tendency toward decreasing river flow (for summer and for low flows especially) contradicts model expectations under assumed global warming scenarios; and the lack of decreasing river flow indicates a robustness and resilience of hydrology to warming trends.
- Khoi and Suetsugi (2012) evaluated seven climate models—CMIP3 GCMs-CCCMA CGCM3.1, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM3.0, UKMO HadGEM1, and UKMO Had CM3—to determine which was most successful in predicting rates of streamflow in Vietnam's Be River Catchment. The IPCC's SRES emission scenarios A1B, A2, B1, and B2 were adopted, along with prescribed increases in global mean temperature ranging between 0.5 and 6°C.

  GCMs consistently have projected increases in the frequency and magnitude of extreme climate events, and variability of precipitation, leading some authors to conclude "this will affect terrestrial water resources in the future, perhaps severely" (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Chen *et al.*, 2011). Khoi and Suetsugi's findings, however, indicate "the greatest source of uncertainty in impact of climate change on streamflow is GCM structure [choice of GCM]," noting the range of uncertainty could have increased even further if a larger number of GCMs had been deployed. Similar findings have been made by other authors, including Kingston and Taylor (2010), Kingston *et al.* (2011), Nobrega *et al.* (2011), Thorne (2011), and Xu *et al.* (2011). Khoi and Suetsugi conclude "single GCM or GCMs ensemble mean evaluations of climate change impact are unlikely to provide a representative depiction of possible future changes in streamflow."

Conclusions

There appears to be little support in real-world data for the contention that CO_2-induced global warming will lead to more frequent and/or more severe increases and decreases in streamflow that result in, or are indicative of, more frequent and/or more severe floods and droughts. Observed trends appear to be just the opposite of what is predicted to occur, and nearly all observed real-world changes are either not deleterious or are beneficial, and often extremely so. For example:

- Lins and Slack (1999) report the United States has become wetter in the mean and less variable in the extremes during warming over the last century.

- Brown *et al.* (1999) have shown the 1999 Mississippi floods were not related to changes in atmospheric CO_2.

- Campbell (2002) demonstrates there is nothing unusual about the moisture status of the Alberta region during the past 50 years compared to the record of the last millennium, and Déry and Wood (2005) similarly record no change in river flows in northern Canada over the past 60 years.

- Pekarova *et al.* (2003) show no long-term changes took place in the discharge of European rivers during the past 180 years, which period encompasses the passage between the end of the Little Ice Age and twentieth century climate.

- Cao *et al.* (2006) could detect no increase in stream discharge on the Tibetan Plateau during recent warming, and Davi *et al.* (2006) could find no evidence for any twentieth century long-term change in precipitation or streamflow.

Clearly, real-world data do not support the negative hydrologic effects the IPCC associates with both real-world and simulated global warming. At the same time, the paper by Khoi and Suetsugi (2012) demonstrates neither single GCMs nor GCM ensembles can currently provide representative estimates of future patterns of streamflow. Moreover, some studies identify solar factors (Brown *et al.*, 1999; Pederson *et al.*, 2001) or multidecadal cyclicity (Hannaford and Marsh, 2008; Mauas *et al.,* 2008) as more important influences on streamflow variability than is atmospheric CO_2.

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6.2. Oceans

Key Findings

The main findings of Section 6.2, Oceans, are:

- SEA-LEVEL CHANGE. Sea-level rise is one of the most feared impacts of any future global warming, but public discussion of the problem is beset by poor data, misleading analysis, an overreliance on computer model projections, and a failure to distinguish between global and local sea-level change—all of which has led to unnecessary and unjustified alarm.
- GEOLOGICAL CONTEXT OF SEA-LEVEL CHANGE. The maximum sustained rate of global sea-level rise during the most recent postglacial melting was about 10 mm/year, or 1 m/century. The main contributions to this rapid rate of rise, which occurred between about 20,000 and 10,000 years ago, came from melting of continental ice caps over North America and northwest Europe. Such ice caps no longer exist, and therefore a value of 10 mm/y is a realistic natural limit for the likely maximum rate of future sea-level rise should further ice melting ensue. More probably, rates will lie close to the observed twentieth century rate of sea-level rise of ~1.8 mm/y from all causes.
- DISTINGUISHING LOCAL FROM GLOBAL (EUSTATIC) SEA LEVEL. Virtually all public discussion that considers sea-level hazard is concerned with changes in the global average sea level. This notional statistic has little relevance to the practicalities of coastal planning and shoreline defense that are the concern of coastal engineers. Real-world coastal management is based upon knowledge of the rate of change of the local relative sea level at the site concerned. Local sea level is influenced as much by substrate subsidence or uplift, sediment supply, and meteorological and oceanographic factors as it is by the notional global average sea level. As it has been in the past, coastal hazard policy should be based upon local relative sea-level change as measured by appropriate and site-specific tide gauges, rather than upon speculative, model-driven prognostications of global average change.
- TIDE GAUGE MEASUREMENTS. Many studies of tide gauge datasets conclude the twentieth century saw a progressive rise in global sea level of between about 1.4 and 1.8 mm/y, modulated at a decadal or multidecadal scale by periods of lesser and greater rates of rise. Such conclusions, however, are based upon corrected tide gauge data, and some analyses of uncorrected data indicate a rate of rise of less than 1 mm/y.
- SATELLITE MEASUREMENTS. Satellite-mounted measurements of sea level made by radar

ranging altimetry have been available since the early 1990s. Until recently, these measurements indicated a rate of global sea-level rise of more than 3 mm/y; i.e., about twice the rate measured by tide gauges. Over the past few years, however, the satellite-measured rate of rise has been closer to 2 mm/y, a figure that may overlap with the tide gauge measurements once errors are taken into account. Nonetheless, and to the degree they continue to indicate higher rates of sea-level rise than do tide gauge datasets, radar altimetric estimates of sea-level change should be treated circumspectly, for the complexity of their processing is so high the accuracy of the method has yet to be fully established.

- NATURAL SEA-LEVEL VARIABILITY. Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and control the oceans' response to atmospheric pressure. These processes vary on decadal and multidecadal time scales, especially with regard to a 60-year-long oceanographic cycle, which vitiates the usefulness of fitting linear trends to sea-level data over periods of less than about 120 years. The pitfall is especially great when shorter periods of time are used to infer an acceleration or deceleration of sea-level rise has occurred, because the existence of such rate changes is an intrinsic part of known natural multidecadal variability. Natural variability must be taken into account during any projection of future sea levels, yet scientists only recently have begun to incorporate it into their modeling.

- ACCELERATION OF SEA-LEVEL RISE. The IPCC's 2007 report projected global sea level was likely to rise by somewhere between 18 and 59 cm by 2100, and at an accelerating rate. Since then, several semi-empirical model analyses have predicted sea-level rises for the twenty-first century might even exceed one meter. However, multiple analyses of tide gauge and satellite records make it clear rates of global rise around 10 mm/y do not, and are not likely to, occur. Nearly all sea-level records show either a steady state of rise or a deceleration during the twentieth century, both at individual locations and for the global average. Though it is only an inadequate 20 years long, the satellite radar altimeter record also displays a recent deceleration of sea-level rise.

- DROWNING ATOLLS. On October 17, 2009, members of the Maldives' Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to oceanic atolls and islands. In contrast, observational and field evidence from a wide geographic range of low-lying ocean islands show low rates of sea-level rise consonant with the tide gauge global average. An oceanic atoll represents a dynamic sedimentary system sustained by broken coral detritus. Atoll integrity is jeopardized when subjected to human environmental pressures such as sand mining, construction project loading, and rapid groundwater withdrawal, all of which cause local lowering of the ground surface. It is these processes in combination with episodic natural hazards such as king tides and storms, not sea-level rise, that provide the alarming footage of marine flooding on Pacific Islands that from time to time appears on television news.

- ISOSTASY. The gravitational load induced on Earth's crust by growth of an ice sheet causes depression of the substrate and local sea-level rise; equally, ice cap melting removes the load and induces uplift and local sea-level fall. This effect is termed isostasy and must be corrected for in global sea-level estimates, generally by using an appropriate Glacial Isostatic Adjustment (GIA). GIA models lack independent verification but are informed by the best-available knowledge of Earth's actual shape, as measured from space in the form of a Terrestrial Reference Frame (TRF). Recently, NASA has indicated current TRF errors are greater than the inferred signal of sea-level change being measured, and the agency has proposed a new satellite be launched with the specific role of measuring the TRF accurately. Clearly, estimates of sea-level change made using satellite-borne altimetric data will remain problematic until the launch of NASA's new GRASP satellite, or until the development of some other mechanism for improving the accuracy of geoid models. As Wunsch *et al.* (2007) noted, "At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology."

- MODELS. Semi-empirical and GCM models of future sea-level change project a logarithmically increasing rate of rise. Their proponents argue that although current sea-level change is slow, this is because the response to temperature has a significant time lag and rates will become progressively faster (10 mm/y or more) in the future. In addition, it is assumed, without justification, that a projected global sea-level curve is also representative of local and regional sea-level changes. The controversy surrounding the likely accuracy and policy usefulness of published semi-empirical and GCM models of sea-level change remains unresolved. Given that simple empirical projections yield more modest projections of future sea level, semi-empirical and GCM model projections indicating higher and increasing rates of rise must be treated as speculative until their known flaws have been addressed.

- MELTING ICE. Accurate measures of the global area of sea ice and the volume of onland ice are available only for the satellite era, commencing in 1979. The complexity of correcting and interpreting data measured from near-Earth space is high, and hence significant uncertainty still attends our knowledge of the water balance of the world's oceans with respect to the melting of onland ice. Nonetheless, no strong evidence exists that either the Greenland or Antarctic ice sheet is wasting at greater than natural rates. Little recent change in global sea level can be attributed to enhanced melting of the modern ice sheets. For Antarctica such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall; in such circumstances the sum of the response of the whole Antarctic Ice Sheet might compensate for any long-term wastage of the Greenland Ice Sheet that might occur. As both Antarctica and Greenland have been cooling for the past half-century, it remains entirely possible the global cryosphere is actually growing in mass.

- OCEAN HEAT. At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 16 years of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming. Increasingly, this problem has been finessed by noting the atmosphere holds only a small percentage of the world's heat, and that what counts is the 93 percent of global heat sequestered in the oceans. Accurate measurements of ocean heat are available only since the 2003 deployment of the Argo system of diving buoys. The available Argo record shows no significant or accelerated ocean warming over the past nine years.

- OCEAN CIRCULATION. It has been asserted global warming will change the speed of major ocean currents such as the Gulf Stream in ways that will make the world's climate less hospitable. Worries also exist that onland ice melting could deliver enhanced volumes of freshwater to the Arctic Ocean and thereby shut down the critical source of sinking saline water that feeds deep water into the world ocean's thermohaline circulation. All components of ocean circulation vary naturally in flow volume or speed, and often in sympathy with climatic factors. No evidence exists for changes in the global ocean circulation system that lie outside the bounds of natural variation. Though this natural variation has yet to be fully described, evidence is lacking for any additional changes in circulation forced by human CO_2 emissions.

Introduction

To assess whether enhanced freshwater delivery to the Arctic Ocean by increased river flow could shut down the ocean's thermohaline circulation, Peterson *et al.* (2002) plotted annual values of the combined discharge of the six largest Eurasian Arctic rivers—Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina, which drain about two-thirds of the Eurasian Arctic landmass—against the globe's mean annual surface air temperature (SAT). They determined a simple linear regression trend through the data and concluded the combined discharge of the six rivers rises by about 212 km3/year in response to a 1°C increase in mean global air temperature. For the high-end global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) to occur by AD 2100—i.e., a temperature increase of 5.8°C—they projected the warming-induced increase in freshwater discharge from the six rivers could rise by as much as 1,260 km3/year (we calculate 5.8°C x 212 km^3/year/°C = 1230 km3/year), a 70 percent increase over the mean discharge rate of the past several years.

It has been hypothesized that the delivery of such a large addition of freshwater to the North Atlantic Ocean may slow or even stop that location's production of new deep water, which constitutes one of the driving forces of the thermohaline circulation, the great oceanic “conveyor belt.”

Although still discussed, this scenario is not as highly regarded today as it was when Peterson *et al.* conducted their research, for several reasons. For one, it is difficult to accept the tremendous extrapolation Peterson *et al.* make in extending their Arctic freshwater discharge vs. SAT relationship to the great length implied by the IPCC’s predicted high-end warming of 5.8°C over the remainder of the current century. According to Peterson *et al.*, “over the period of the discharge record, global SAT increased by 0.4°C.” It is implausible to extend the relationship they derived for that small temperature increase fully 14-and-a-half times further, to 5.8°C.

Consider also the Eurasian river discharge anomaly vs. global SAT plot of Peterson *et al.* (their Figure 4), which we have re-plotted in Figure 6.2.1. Enclosing their data with simple straight-line upper and lower bounds, it can be seen the upper bound of the data does not change over the entire range of global SAT variability, suggesting the upper bound corresponds to a maximum Eurasian river discharge rate that cannot be exceeded in the real world under its current geographic and climatic configuration. The lower bound, by contrast, rises so rapidly with increasing global SAT that the two bounds intersect less than two-tenths of a degree above the warmest of Peterson *et al.*’s 63 data points, suggesting 0.2°C beyond the temperature of their warmest data point may be as far as any relationship derived from their data may be validly extrapolated.

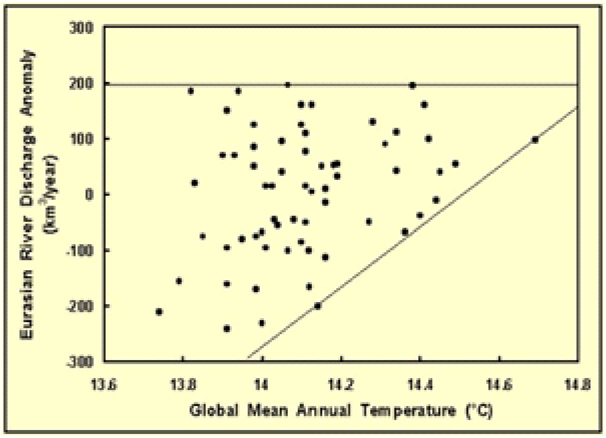

Figure 6.2.1. Annual Eurasian Arctic river discharge anomaly vs. annual global surface air temperature (SAT) over the period 1936 to 1999. Adapted from Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.

Reference

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6.2.1. Sea-level Change

Sea-level rise is one of the most feared impacts of any future global warming (Nicholls, 2011). But public discussion of the problem is beset by poor data, misleading analysis, and an overreliance on computer model projections, leading to unnecessary alarm.

A proper understanding of the risks associated with sea-level change can be attained only by maintaining a clear distinction between changes in global sea level (often also called eustatic sea level) and changes in local relative sea level. Sea-level changes are measured relative to a defined reference level, or datum. This datum is difficult to define over regional and global scales because Earth’s surface is not static; it deforms at different rates and scales in different places. At any one time, the sum of such dynamics controls the volume of the global ocean basin and, therefore, for a fixed volume of seawater, dictates the average sea level worldwide. At the same time, and because both the dynamic Earth surface and the volume of seawater change through time, in combination they also control the multiplicity of local rates of sea-level change we actually observe.

The possibility of large and damaging sea-level rises caused by human-related global warming features prominently in presentations by those who call for urgent action to “stop” global warming, such as former U.S. Vice President Al Gore (Gore, 2006).

Past sea-level positions are measured or inferred from geological evidence. Factual observations regarding modern sea level and its change are traditionally made using tide gauges. Since the early 1990s, modern sea level also has been measurable independently by radar-ranging from satellites.

When data from these sources are analyzed, rates of sea-level change, either rises or falls, are found to vary through time and space (geography), and often quite dramatically over geological time scales. We discuss below several matters relevant to the assertion of both natural and possible human-caused sea-level rise, organizing the discussion into sections that address observations, modeling, mechanisms, and policy. *Inter alia*, we examine historical trends in sea level to see if any recent increase has occurred in global sea level in response to the supposedly unprecedented warming of the planet over the twentieth century; discuss the proposed scenarios whereby either melting ice or a warming ocean might cause sea levels to rise; and consider the important questions of decadal and multidecadal variability in rates of sea-level change, including both accelerations and decelerations of the rate of change.

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Nicholls, R.J., 2011. Planning for the impacts of sea-level rise. *Oceanography* **24**(2): 144–157.

6.2.1.1. Geological studies

Changes in sea level over long periods of time (millions of years) are inferred from geological evidence. By their nature, most such records are of local relative change, and they require correction if they are to be translated into eustatic estimates (e.g., Kominz *et al.*, 1998).

For about the past 3 million years a high-quality proxy record for eustatic sea level is represented by the oceanic oxygen isotope record (e.g., Lisiecki and Raymo, 2006; see Figure 6.2.1.1.1). This curve is based on the measured ratio of two isotopes, ^{16}O and ^{18}O, that are fractionated in seawater and hence vary in the shells of fossil animals that lived in that water in accordance with fluctuations of global ice volume through time. High-resolution (millennial) oxygen isotope curves from all ocean basins and latitudes contain a common signal pattern that has become a standard for subdividing Quaternary time into climatic Marine Isotope Stages (MIS), numbered backwards through time. The present interglacial (termed the Holocene and defined as starting 11,700 years ago) is effectively synonymous with MIS 1.

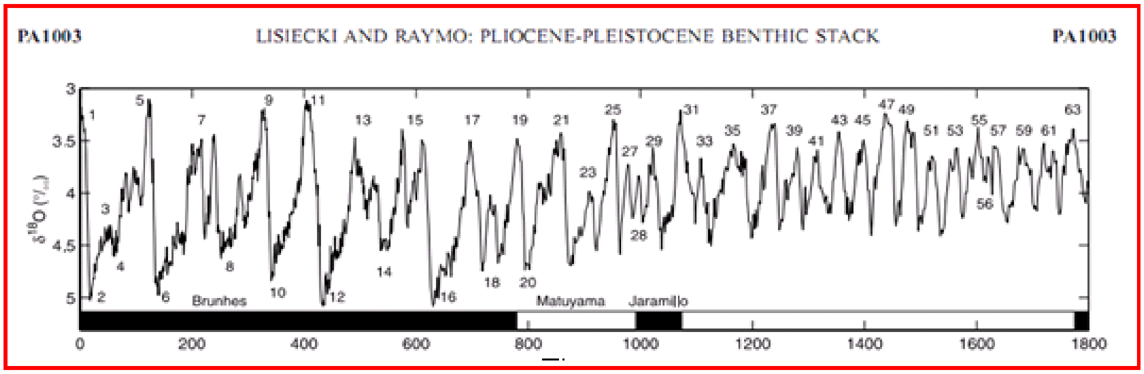

Figure 6.2.1.1.1. Oxygen isotope curve showing the major climatic fluctuations of the last 1.8 million years; numbered peaks indicate Marine Isotope Stages, with even numbers corresponding to ice ages and odd numbers to warm interglacials. A full glacial-interglacial range, say between MIS 12 and MIS 11, represents about 120 m of sea-level change. The apparent anomaly of MIS 3 carrying the designation that otherwise equates to a full interglacial interval stems from the early believe that ice ages were paced by variations in the Earth's 41,000 obliquity cycle. Adapted from Lisiecki, L.E. and Raymo, M.E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic del-^{18}O records. *Paleoceanography* **20**: PA1003. doi: 10.1029/ 2004PA001071.

The last ice age reached its peak about 20,000 years ago, at which time sea level stood at about -120 m with respect to today. Efforts have been made to reconstruct a global sea-level curve for the period since then, based on careful geological sampling and dating of sea-level-related materials such as mangroves or coral reefs. The resulting curve, in Figure 6.2.1.1.2, shows very rapid melting, at rates up to 26 mm/y over short periods between about 15,000 and 10,000 years ago, after which the rate of rise lessens to 1–2 mm/y in the Holocene.

It is important to note glacio-isostatic effects may have distorted or invalidated the key proxy sea-level records that have been used to construct Figure 6.2.1.1.2 and similar post-glacial sea-level curves (Gehrels, 2010). For example, Bowen (2010) has shown tectonic effects have resulted in a range of

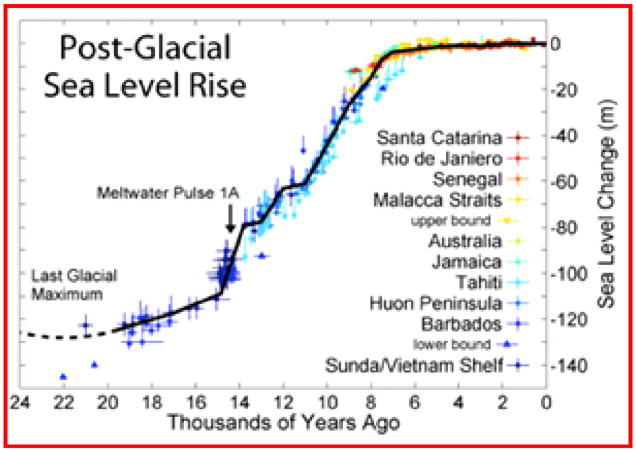

Figure 6.2.1.1.2. Reconstructed global sea-level since the Last Glacial Maximum, 20,000 years ago, based on dated worldwide coral and peat deposits. Adapted from Fairbanks, R.G. 1989. A 17,000 year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**: 637–642; Toscano, M.A. and Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmate* framework and intertidal mangrove peat. *Coral Reefs* **22**: 257–270.

estimates for sea level during warm interglacial MIS 11, most of which do not support the high +20 m level some previous authors have estimated but instead lie closer to present day sea level. It is the presence of significant regional variations in the timing and shape of the sea-level curve, particularly over the past 7,000 years, that led Gehrels (2010) to suggest "'Eustasy' is therefore merely a concept, not a measurable quantity."

Ignoring these geological perspectives, the first reports by the IPCC claimed human-forced sea-level rise could reach as high as 2–3 m by the year 2100 (Hoffman *et al.*, 1983; Kaplin, 1989). Although subsequent IPCC reports have lowered the sea-level rise estimate to something more realistic, individual authors continue to promulgate potential sea-level rises of 1–2 m or more by 2100 AD, supposedly caused by exceptional melting of ice in the Greenland and Antarctic ice caps (e.g., Rapley, in Doyle, 2007; Rahmstorf, 2007).

Hansen and Sato (2011) claimed sea level will rise 5 m by 2100 AD and proposed an exponential increase in glacier melting would produce a 4 m rise in sea level in the 20-year period from 2080 to 2100, a rate of 200 mm/year. These frenetic estimates are made notwithstanding that the Antarctic ice cap has expanded, not decreased, in the past 20 years (see Chapter 5) and the Greenland ice cap was about the same size as today during the 2.5 °C warmer Holocene Climatic Optimum (Willerslev *et al.*, 2007).

In a number of papers Nils-Axel Mörner (1983, 2004, 2011) has established a maximum possible glacial eustatic rate of change of 10 mm/yr, or 1.0 m/century, derived from the rates that occurred during the glacial eustatic rise after the last glaciation maximum (LGM) of the Last Ice Age at around 20 ka with a sea-level lowstand of about 120 m. The main contribution to the large post-glacial rise in sea level came from melting of the continental ice caps over North America and northwest Europe. a value of 10 mm/yr sets a realistic natural frame for possible maximum rates of modern sea-level rise that might ensue should ice-cap melting quicken.

More generally, it is important to address critically the degree to which sea-level changes on geological timescales can be used to predict future change. Past changes are reconstructed from geologic and geomorphic evidence along coastlines and from inferences drawn about changing ocean geochemistry (^{18}O/^{16}O ratios measured on marine microfossils in cores). These are very different lines of evidence, and interpretation of the geochemical studies is further complicated by shifting isotope ratios being caused not only by temperature, but also by water exchanged between the oceans and ice caps during climate cycling. While the temperature term can be removed for some samples using Mg/Ca measurements, the hydrographic effect remains uncertain. Therefore, while an averaged δ^{18}O signal of global variability provides an overall indication of the magnitude of glacials and interglacials, as shown in Figure 6.2.1.1.1 above, it is difficult to be confident such data can provide an accurate guide to sea-level variability when differences of at most a few meters are involved for future prediction.

Similar uncertainty presents itself when estimates of lowered sea level and its timing are estimated for the Last Glacial Maximum in order to calibrate sea-level change represented in the δ^{18}O record. Lowstand estimates range from -130 m at 20,000 yrs ago (Yokoyama *et al.*, 2000) to -120 m 26,000 yrs ago (Peltier and Fairbanks, 2006). These differences may be caused by regional variability (Elderfield *et al.*, 2012), but they make clear the difficulty of acquiring accurate sea-level estimates. Estimates derived from calculating the effects of glacial isostatic readjustment (GIA) after the last ice age, especially for far field locations, are uncertain. Variability in time and space of the water content of the mantle (especially olivine) influences its viscosity, which in turn controls isostatic response and is poorly understood (Jones *et al.*, 2012).

Conclusions

Geological evidence provides an important knowledge framework but seldom offers the accuracy and precision needed to inform estimates in the decimeter to several-meter range likely to apply to near-future sea-level rise. Moreover, projections of sea-level change out to 2100 AD must be considered within the framework set by the known maximum rate of post-glacial sea-level rise, 10 mm/yr (1 m/century). Likely rates of future sea-level rise following melting of the Greenland and/or Antarctic ice caps fall well below this 10 mm/yr figure and probably will lie close to the observed modern level of sea-level rise of ~1.8 mm/yr from all causes.

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Earlier Research

Summarized briefly below are other recent papers that approach the sea-level issue from a geological viewpoint.

- Mörner (2004) noted "prior to 5000–6000 years before present, all sea-level curves are dominated by a general rise in sea level in true glacial eustatic response to the melting of continental ice caps"; given the slowdown of this process thereafter, "sea-level records are now dominated by the irregular redistribution of water masses over the globe ... primarily driven by variations in ocean current intensity and in the atmospheric circulation system and maybe even in some deformation of the gravitational potential surface." With respect to the past 150 years, Mörner reports the mean eustatic rise in sea level for the period 1850–1930 was 1.0–1.1 mm/year, but "after 1930–40, this rise seems to have stopped until the mid-1960s (Pirazzoli *et al.*, 1989; Mörner, 1973, 2000)." Thereafter, with the advent of the TOPEX/Poseidon mission, Mörner notes "the record can be divided into three parts: (1) 1993–1996 with a clear trend of stability, (2) 1997–1998 with a high-amplitude rise and fall recording the ENSO event of these years and (3) 1998–2000 with an irregular record of no clear tendency." Importantly, Mörner concludes "there is a total absence of any recent 'acceleration in sea-level rise" and, therefore, "no fear of any massive future flooding as claimed in most global warming scenarios."

- The PALeo SEA Level Working Group (PALSEA, 2009, 2012) of 32 experienced researchers was convened to examine and summarize the records of recent geological scale sea-level change to provide context for speculations regarding future sea-level rise. With respect to the IPCC's estimate that global warming between 1.1°C and 6.3°C will occur in the twenty-first century, the group points out the last global warming of comparable magnitude occurred during the termination of the last glacial period. That warming consisted of a series of short, sharp steps on millennial to centennial timescales, the magnitude and rate of warming of which are closely analogous to those of the anthropogenic warming predicted to occur over the coming centuries. This comparison immediately rules out any type of exponentially increasing sea-level response, pointing more toward an asymptotic response where sea-level rise is high initially but gradually levels off (Figure 6.2.1.1.3).

Extending the time scale to the 11,700-year Holocene period, the PALSEA team identified rapid warming and eustatic sea-level rise between 9 and 8.5 ka BP and 7.6 and 6.8 ka BP (increases of 1.3 and 0.7 m per century, respectively). Although a "rapid demise of ice sheets in a climate similar to today is certainly a possibility," they note, "an improved understanding of ice sheet dynamics is required before one can conclude that the Greenland or West Antarctic ice sheets will behave in a similar fashion in the future." The PALSEA group noted peak sea levels during the last interglacial period were about 3–6 m above modern sea level at 126 ka BP but attained these highs only "several thousand years after proxy records of temperature reached interglacial levels."

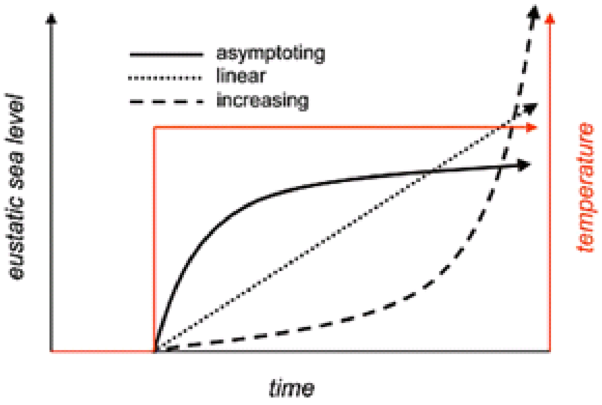

Figure 6.2.1.1.3. Three alternative models for sea-level rise. Adapted from PALSEA, 2009. The sea-level conundrum: case studies from palaeo-archives: *Journal of Quaternary Science* **25**: 19–25.

Overall, if the worst-case warming scenario of the IPCC were actually to occur, the PALSEA scientists conclude the likely sea-level rise would lie between the lower limit of twentieth century sea-level rise (0.12 m per century) and sea-level rise at the conclusion of the last glacial period (1 m per century).

- Yokoyama and Esat (2011) note climate change does not always produce a measurable sea-level response, but when it has, that response was rapid and usually accompanied by shifts in ocean circulation.
- Stanford *et al.* (2011) found the most likely maximum rates of sea-level rise during the post-glacial melting ranged from 13 to 15 mm/y, perhaps peaking at 26 mm/y for short periods (decades at most). The maximum rates of rise occurred in two short bursts, referred to as melt-water pulses, that appear to be linked to breakout floods from large Northern Hemisphere pro-glacial lakes. As no large meltwater lakes exist today, such high rates of rise are unlikely to be repeated.

Conclusions

The conclusions drawn from geological evidence contradict the logarithmically increasing sea-level response assumed by the empirical and semi-empirical models used by the IPCC. Some researchers have used the output of these models to generate alarm by saying currently observed sea-level change is slow only because of a lagged response to temperature forcing; they contend sea-level rise will become progressively faster (10 mm/y or more) in the future. Furthermore, some researchers assume, without justification, that a projected global eustatic sea-level curve is indicative of local or regional sea-level changes.

Natural geological constraints mean predictions of sea-level changes between now and 2100 AD must fall within the frames set by the post-last-glaciation-maximation rates of sea-level rise: less than 10 mm/yr. Any near-future rate of melting of the Greenland and/or Antarctic ice caps is likely to fall well below the rate of the major post-glacial warming.

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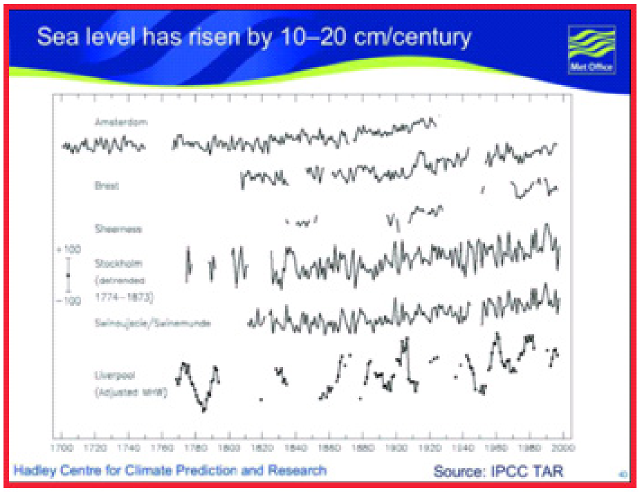
6.2.1.2. Tide gauges

Local relative sea level traditionally has been measured at ports using tide gauges, some of which have records extending back to the eighteenth century (see Figure 6.2.1.2.1). These measurements tell us about the change occurring in actual sea level at particular coastal locations, including rises in some places and falls at others. After correcting for any site-specific tectonic or oceanographic-meteorologic distortions of the underlying eustatic sea-level signal, a number of geographically dispersed tide gauge records can be averaged to provide an estimate of the global sea-level curve.


Sea level has risen by 10–20 cm/century

Hadley Centre for Climate Prediction and Research

Source: IPCC TAR

Figure 6.2.1.2.1. Long, northern hemisphere tide gauge records of sea-level change, 1700–2000. Adapted from Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001. 3rd Assessment Report of the IPCC.*

Tide gauges measure water-level oscillations, not merely changes in mean sea level. Various techniques are used to filter out the influence of unwanted oscillations (Pugh, 2004). The tide gauge is constructed in such a way that the instrument gives a limited response to short-duration oscillations such as swell waves and vessel wakes. Numerical techniques are used to extract the oscillations of interest. The analysis generally is optimized to extract tidal constituents, which is not ideal for assessing long-term sea-level changes, particularly since some tidal constituents have periods of years to decades.

After correcting for these factors and for subsidence or uplift, the longer-term tide-gauge records indicate a twentieth century sea-level rise of +1–2 mm/y. Based on these records, the IPCC (2001) estimated an average rate of eustatic rise between 1900 and 2000 of 1.6 mm/y. However, the derivation of such a rate of change is usually achieved by least-squares linear trend analysis. Such calculations are highly sensitive to the start and end points selected for the dataset being considered, and they ignore short-term and multidecadal changes in sea level known to be associated with meteorological and oceanographic oscillations such as ENSO and the Pacific Decadal Oscillation.

Despite the “consensus” adoption of 1.6–1.8 mm/y as the most likely rate of sea-level rise estimated from tide gauge records, Goddard (2013) recently has shown a straight averaging of the trends of the 159 tide gauge records represented in the NOAA tidal database indicates a much lower figure of only 0.7 mm/y, Similarly low rates of 0.5–1.2 mm/y over historic or late Holocene periods also have been reported by several other authors (Burton, 2010; Gehrels and Woodworth, 2013; Miller *et al.*, 2009; Mörner, 2004, 2012).

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Earlier Research

That global average sea level has been rising gently for the past 100+ years has been established by observation. The precise rates of change and the degree to which those rates vary through time remain open questions in the research literature. Some of the many papers that bear on the topic are summarized below.

- Cazenave *et al.* (2003) studied variation in global sea level on interannual to decadal time scales, focusing on the thermal expansion of the oceans and the continental water mass balance. They determined a rate of thermosteric sea-level rise over the previous 40 years of about 0.5 mm/year. They note, however, 1993–2000 analyses of TOPEX-Poseidon altimetry data and the global ocean temperature data of Levitus *et al.* (2000) both yielded rates of rise approximately six times greater than their inferred rate. They interpreted this to mean “an acceleration took place in the recent past, likely related to warming of the world ocean.” Other interpretations acknowledged by Cazenave *et al.* are that “the recent rise may just correspond to the rising branch of a decadal oscillation” and “satellite altimetry and in situ temperature data have their own uncertainties and it is still difficult to affirm with certainty that sea-level rise is indeed accelerating.” On this second point, Nerem and Mitchum (2001) indicate at least 20 years of satellite altimetry data are necessary to detect an acceleration in sea-level rise).
- Jevrejeva *et al.* (2006) analyzed information in the Permanent Service for Mean Sea Level data-base using a method based on Monte Carlo Singular Spectrum Analysis, designed to remove 2- to 30-year quasi-periodic oscillations to derive nonlinear long-term trends for 12 large ocean regions. These curves were combined to produce the mean global sea level (upper) and rate-of-rise (lower) curves depicted in Figure 6.2.1.2.2. The figure shows no acceleration of sea-level rise since the end of the Little Ice Age around 1860. Jevrejeva *et al.* say “global sea-level rise is irregular and varies greatly over time” but “it is apparent that rates in the 1920–1945 period are likely to be as large as today’s.” In addition, they report their “global sea-level trend estimate of 2.4 ± 1.0 mm/year for the period from 1993 to 2000 matches the 2.6 ± 0.7 mm/year sea-level rise found [then] from TOPEX/Poseidon altimeter data.”
- White *et al.* (2005) compared estimates of coastal and global averaged sea level for 1950 to 2000, confirming earlier findings of “no significant increase in the rate of sea-level rise during this 51-year period.” They note several earlier investigators (Douglas, 1991, 1992; Maul and Martin, 1993; Church *et al.*, 2004; Holgate and Woodworth, 2004) similarly concluded the measured rate of global sea-level rise was rather stable over the past hundred years, in contrast to the climate model projections for an increase in rate during the twentieth century.

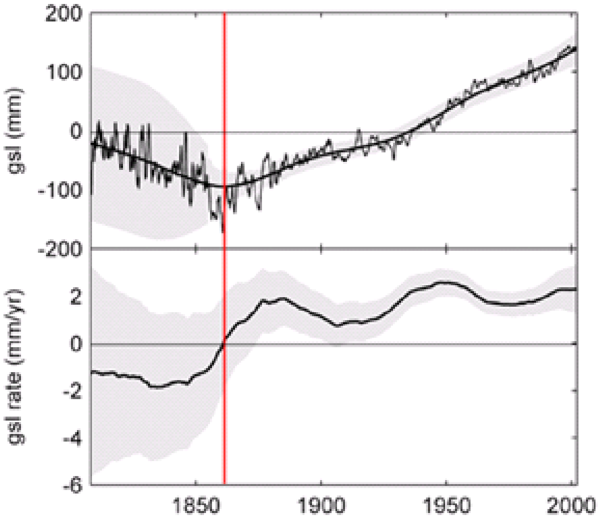

Figure 6.2.1.2.2. Mean global sea level (top), with shaded 95% confidence interval, and mean rate-of-rise (bottom), with shaded standard error interval. Adapted from Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S. 2006. Nonlinear trends and multiyear cycles in sea-level records. *Journal of Geophysical Research* **111**: C09012, doi:10.1029/2005JC003229, 2006.

- Aiming to improve the correction of tide gauge data for vertical substrate motion, Wöppelmann *et al.* (2009) analyzed GPS vertical velocities from a global network of 227 stations between 1997 and 2006. Of the stations they studied, 160 were located within 15 km of an established tide gauge. Assuming land motion is essentially linear over the time span considered, Wöppelman *et al.* used the GPS vertical velocities they derived "to correct for the land motion affecting the tide gauge records to derive absolute (geocentric) changes in sea level." They obtained a global-average rate of geocentric sea-level rise for the past century ranging from 1.55 to 1.61 mm/year, depending on whether one outlier (of 28 individual regions) was included or omitted from their analysis. Wöppelmann *et al.* conclude their result is "in good agreement with recent estimates" such as Church and White (2006; 1.7 mm/yr), Holgate (2007; 1.7 mm/yr), and Leuliette and Miller (2009; 1.5 mm/yr for 2003–2007, using satellite altimetry, Argo, and GRACE gravity observations to estimate the sum of the thermosteric and land ice contributions to sea-level rise).
- Wenzel and Schroter (2010) used a method of neural net analysis in a novel attempt to resolve problems such as tectonic movement or missing data at individual stations. Using 56 tidal stations with at least 50 years of data each, the researchers first corrected the data for substrate movement up or down. The training data used for the neural net were three sets of altimetry data for recent decades, and all three results were shown. Wenzel and Schroter found no net trend in sea level for the South Atlantic and tropical Indian Oceans and a net decline for the Southern Indian Ocean. The Pacific Ocean showed an approximate 70-year oscillation in sea level that correlates (with lag) with the Pacific Decadal Oscillation, while the Atlantic showed cycles of 23 and 65 years. Overall, ocean basin changes showed lagged correlations with the PDO and Southern Annular Mode indices.

  Averaging these results over the globe as a whole, Wenzel and Schroter arrived at a linear upward sea-level trend of 1.56 mm/year with no sign of recent acceleration. Their results agree with those of Hagedoorn *et al.* (2007) of 1.46 mm/year and Wöppelmann *et al.* (2009) of 1.61 mm/year, as well as other recent studies that give only slightly higher values, around 1.7–1.8 mm/year.
- In another novel approach, Church *et al.* (2011) compared results from tide gauge and satellite altimeter measurements. They based their approach on solving Earth's sea-level and energy budgets together in a consistent manner, using the latest available data for the period 1972–2008. They found good agreement between the mean annual sea-level and energy budgets, as illustrated in Figure 6.2.1.2.3. They observed, "from 1972 to 2008, the observed sea-level rise [1.8 ± 0.2 mm/year from tide gauges alone and 2.1 ± 0.2 mm/year from a combination of tide gauges and altimeter observations] agrees well with the sum of energy budget contributions (1.8 ± 0.4 mm/year) in magnitude and with both having similar increases in the rate of rise during the period."

Conclusions

These studies generally suggest the twentieth century has seen a steady rise in global sea level of between about 1.4 and 1.8 mm/yr, albeit modulated at a decadal or multidecadal scale.

This raises an obvious question: If the late twentieth century global warming was as extreme as the IPCC claims it has been, why can it not be detected in global sea-level data? The effects of the warming that led to the demise of the Little Ice Age—which the IPCC contends should have been considerably less dramatic than the warming of the late twentieth century—are readily apparent from the work of Jevrejeva *et al.* shown in Figure 6.2.1.2.2 above; they show a broad similarity in sea-level

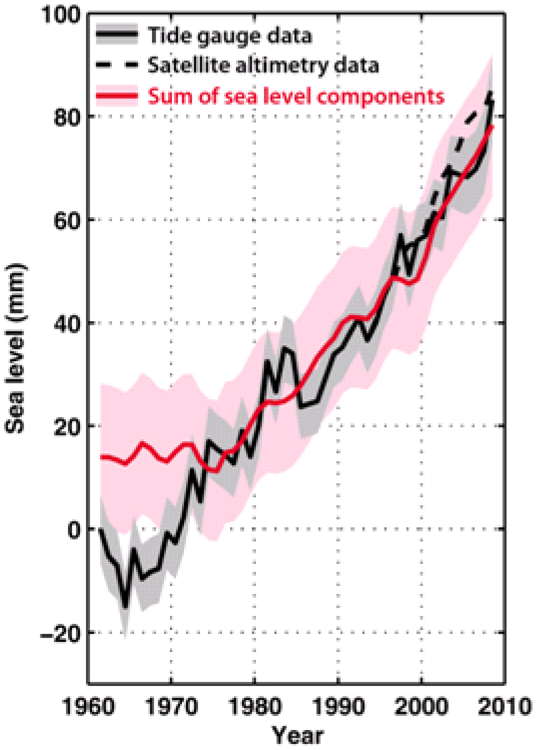

Figure 6.2.1.2.3. Mean global sea level vs. time, as derived from tide gauge data, satellite altimetry data and summing of the individual contributory components to sea level rise. Adapted from Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/ 2011GL048794.

response throughout the 150-year-long post-LIA period, with a lessening of the rate of rise for the 1960s through the 1980s.

Similarly, although the rate of increase in atmospheric carbon dioxide levels grew dramatically just after 1950, shifting from a 1900–1950 mean rate of rise of 0.33 ppm/year to a 1950–2000 mean rate of rise of 1.17 ppm/year, the mean global sea-level rate of rise did not trend smoothly upwards after 1950.

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6.2.1.3. Satellites

Since the early 1990s, sea-level measurements have been made by microwave radar and laser ranging from various orbiting satellites, including the U.S. TOPEX-Poseidon, the European Remote-Sensing Satellite (ERS), Geosat Follow-On (GFO), EnviSat, and Jason series. Situated in polar geostationary orbit, these satellites are able to make repeat measurements of the exact distance to the sea surface at locations across the globe over cycles varying between three and 35 days as Earth rotates below the satellite (see Figure 6.2.1.3.1).

Thus, like tide gauge measurements although with almost complete coverage between 66° N and 66° S, satellites measure changing sea-level heights through time and therefore provide many records of sea-level change at different places (see Figure 6.2.1.3.2), which subsequently can be averaged into an estimate of global sea-level change over a specified period (Figure 6.2.1.3.3).

Averaging the repeat measurements for each location removes the effects of tides and waves. The nominal accuracy of about +/- 100 mm can be improved to about +/- 40 mm by averaging 10-day-separated repeat measurements, or +/- 20 mm for monthly averages, at particular locations (Leuliette and Willis, 2011; Leuliette, 2012). This accuracy is not fully secure because we lack knowledge of the benchmark reference frame for the shape of Earth, the geoid, as well as other uncertainties introduced by the need for corrections for orbital drift and decay and for the stitching together of records from different successive satellites.

Both satellite and tide gauge data are used to estimate the rates of sea-level change over time by fitting a statistical model to the data, usually a linear model. The overall gradient of the resulting model fit is the estimate of the rate of sea-level change. There are complications with undertaking this type of analysis, including the errors associated with each data point and serial correlation of the measurements.

For time-series of sea-level data, successive measurements are often correlated with preceding data because there are repeating patterns, and as sea-level changes, the next measurement is more likely to change in the same direction than in the opposite direction. This increases the uncertainty in the estimates of the slope and is not always accounted for. Further, the slope is usually quoted to a greater precision than the data (e.g., 0.1 mm for satellite data with an accuracy of about 20 mm), which can give a misleading impression of the accuracy of the estimated rate of sea-level rise.

It is important to note satellites and tide gauges do not measure quite the same thing. Tide gauges measure relative to a fixed land benchmark (usually the mean tide level), while satellites measure relative to a mathematical model of the shape of Earth's gravity field (geoid) that is not well characterized and varies over time. Accordingly, a component of satellite "sea-level change," perhaps as much as 50 percent, actually results from geoid changes.

Given these uncertainties, it is not surprising to find the satellite measurements yield an estimate of the rate of global sea-level change that differs from the tide gauge record, indicating an almost doubled rate of rise of more than 3mm/y. The main cause of this discrepancy is likely geoid inaccuracy (see Section 6.2.1.8 below).

Our discussion so far has centered on data collected and processed by NOAA's U.S.-based satellite fleet as presented at the NOAA Laboratory for Satellite Altimetry Web site (NOAA LSA, 2012) (Figure 6.2.1.3.3). But another problem with satellite-borne measurements is that significant differences occur among the sea-level curves reconstructed using different sensors and by different research groups.

For the period 2002–2012, independent sea-level measurements were conducted using the European Space Agency's (ESA) ENVISAT satellite. Until shortly before its failure in 2012, the 2004-onward ENVISAT record (Figure 6.2.1.3.4) persistently displayed a lower rate of sea-level rise than that indicated by U.S. measurements (Figure 6.2.1.2.3).

In June 2012, a new posting of an extended (back to 2002) ENVISAT sea-level curve was made (see Figure 6.2.1.3.5). For the new curve, corrections were made by reprocessing data and incorporating an unspecified "instrumental correction" of +2 mm/y. These corrections increased the "measured" ENVISAT rate of sea-level rise from 0.76 mm/y to 2.33 mm/y, bringing the ESA's results more in line with those of NOAA. Meanwhile, since early 2011, the NOAA data themselves had been adjusted toward a higher rate of sea-level rise by the addition of a +0.3 mm/y glacial isostatic (GIA) adjustment.

It is of course entirely possible the calibration and correction procedures used for any particular satellite instrument package are in error, and that later data adjustments are therefore justified when this is discovered—and perhaps especially so given that

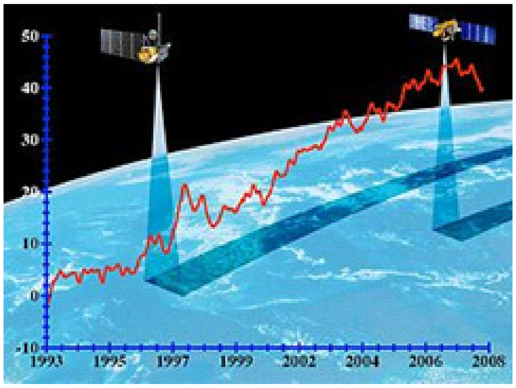

Figure 6.2.1.3.1. Graphic depicting NOAA satellite collecting sea-level data using radar altimetry, 1993–2008. Adapted from NASA.

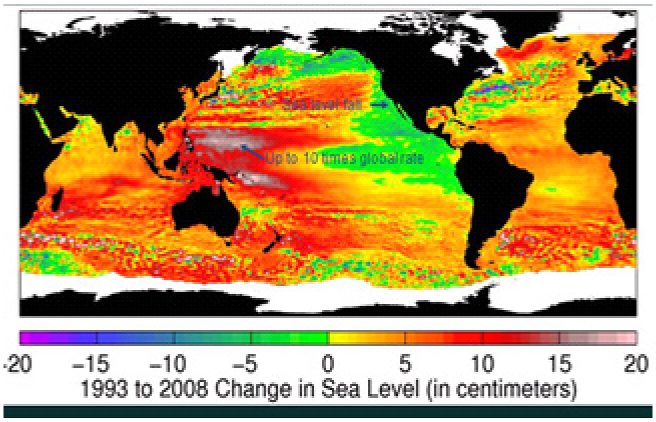

Figure 6.2.1.3.2. Sea-level rise is spatially very non-uniform. Synoptic global map of rate of sea-level change 1993-2008, as measured by radar altimetry. Adapted from NOAA.

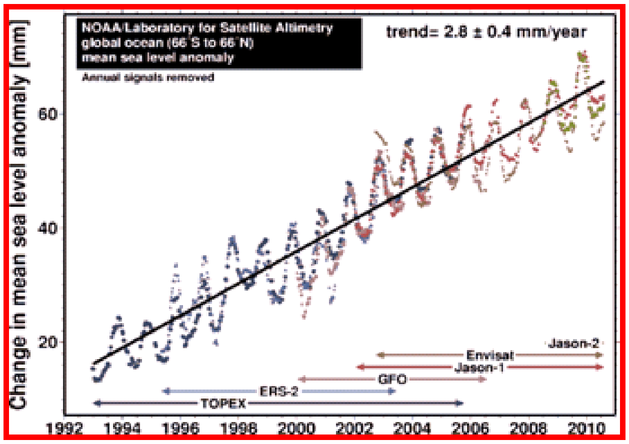

Figure 6.2.1.3.3. NOAA satellite altimetry, global sea-level change since 1992. Dataset composite, collected from successive satellites (coded in color) and plotted monthly.

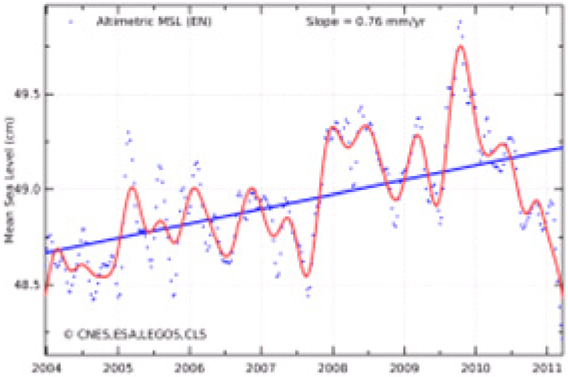

Figure 6.2.1.3.4. ENVISAT sea-level record with fitted trend line of +0.76 mm/y, 2002–2012. Adapted from Watts, A. 2012. ENVISAT's satellite failure launches mysteries. http://wattsupwiththat.com/2012/04/12/envisats-satellite-failure-launches-mysteries/.

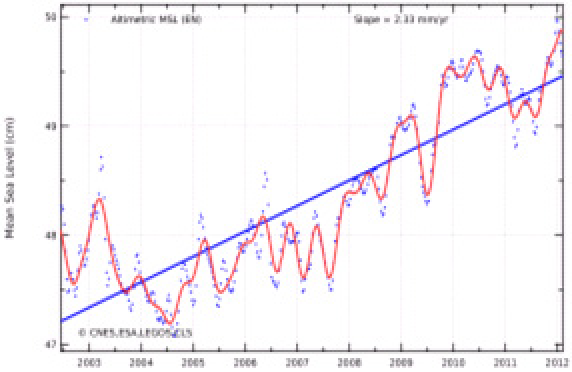

Figure 6.2.1.3.5. Arbitrarily adjusted ENVISAT sea-level record with fitted trend line of +2.33mm/y, 2004-2012 (after Watts, 2012).

ENVISAT persistently had been recording lower rates of rise than other satellites. But it is also disturbing that such adjustments nearly always seem to result in *increases* in the rate of sea-level rise determined; given a significant number of different arbitrary corrections, one might expect about one-half would increase and one-half lessen the rate of rise.

Government science agencies around the world often argue for "correction" of data to bring them into line with a preconceived result. New Zealand's crown research agency, the National Institute of Water and Atmospheric Research (NIWA), has suggested all New Zealand tide gauge records should have a GIA adjustment of +0.4 mm/y to bring the regional Southwest Pacific rate of sea-level rise into line with the global estimate of 1.8 mm/y. This contradicts the recommendation that sea-level rise should be assessed regionally and not in terms of a poorly constrained global average (Gehrels, 2010).

Conclusions

To the extent satellite altimetric measurements continue to return rates of sea-level rise greater than 2 mm/yr, and especially greater than 3 mm/yr, the results must remain suspect, because such high rates conflict with the well-established twentieth century rates of 1–2 mm/yr calculated from tide gauge data.

The mismatch between satellite and tide gauge records was addressed by Wunsch *et al.* (2007), who point out "the widely quoted altimetric global average values may well be correct, but the accuracies being inferred in the literature are not testable by existing in situ observations." Using modeling, they derived an alternative global mean sea-level change estimate for 1993–2004 "of about 1.6 mm/y, or about 60% of the pure altimetric estimate, of which about 70% is from the addition of freshwater." This rate of change is very close to that indicated by the tide gauge records.

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Earlier Research

The reconstruction of sea-level curves from satellite altimetric data remains a vigorous field of study. We summarize below three important earlier papers in the field.

- Church *et al.* (2004) used TOPEX/Poseidon satellite altimeter data to estimate global empirical orthogonal functions, which they combined with historical tide gauge data to estimate monthly distributions of large-scale sea-level variability and change over the period 1950–2000. They estimated the globally averaged sea-level rise for the last half of the twentieth century at 1.8 ± 0.3 mm/year, a figure in close agreement with tide gauge estimates. In addition, they note "decadal variability in sea level is observed, but to date there is no detectable secular increase in the rate of sea-level rise over the period 1950–2000." They conclude there was no increase in the rate of sea-level rise for the entire twentieth century, citing the work of Woodworth (1990) and Douglas (1992).
- Cazenave and Nerem (2004) seem to dismiss the caution shown by Cazenave *et al.* (2003) in claiming "the geocentric rate of global mean sea-level rise over the last decade (1993–2003) is now known to be very accurate, 2.8 ± 0.4 mm/year, as determined from TOPEX/Poseidon and Jason altimeter measurements." Placing faith in this result leads them to note "this rate is significantly larger than the historical rate of sea-level change measured by tide gauges during the past decades (in the range of 1–2 mm/year)." Nonetheless, they concede "the altimetric rate could still be influenced by decadal variations of sea level unrelated to long-term climate change, such as the Pacific Decadal Oscillation, and thus a longer time series is needed to rule this out."

  Importantly, because it is often ignored, Cazenave and Nerem also note satellite altimetry reveals a "non-uniform geographical distribution of sea-level change, with some regions exhibiting trends about 10 times the global mean" (see Figure 6.2.1.3.2). Regional differences are also highlighted by the fact that "for the past 50 years, sea-level trends caused by change in ocean heat storage also show high regional variability." Cazenave and Nerem report "these [satellite altimetric] tools seem to have raised more questions than they have answered."
- Carton *et al.* (2005) note "recent altimeter observations indicate an increase in the rate of sea-level rise during the past decade to 3.2 mm/year, well above the centennial estimate of 1.5–2 mm/year," noting further "this apparent increase could have resulted from enhanced melting of continental ice or from decadal changes in thermosteric and halosteric effects." Using a new eddy-permitting Simple Ocean Data Assimilation version 1.2 reanalysis of global temperature, salinity, and sea level for the period 1968–2001, they determined "the effect on global sea-level rise of changing salinity is small except in

subpolar regions." They also found warming-induced steric effects "are enough to explain much of the observed rate of increase in the rate of sea-level rise in the last decade of the twentieth century without need to invoke acceleration of melting of continental ice."

It follows, as determined also by Lombard *et al.* (2005), that the high rate of global sea-level rise observed over the past decade is probably a transient result of the global ocean's thermal behavior. Consequently, and in harmony with the findings of Levitus *et al.* (2005) and Volkov and van Aken (2005), there is no need to invoke the melting of land-based glacial ice to explain the observed recent increase in global sea level.

Conclusions

Estimates of sea-level change made using satellite-collected data remain problematic because, among other reasons, they are heavily dependent on the accuracy of a GIA adjustment that lacks independent verification (Houston and Dean, 2012). Summarizing comparisons between the tide gauge and satellite altimeter studies, Houston (2013) concludes, "[It] cannot be determined yet whether the greater trend measured by the altimeters and tide gauges from 1993 to 2011 is the leading edge of a sustained rise or a fluctuation similar to others that have occurred in the twentieth century."

As Wunsch *et al.* (2007) noted:

> At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology. The most urgent job would appear to be the accurate determination of the smallest temperature and salinity changes that can be determined with statistical significance, given the realities of both the observation base and modeling approximations. Both systematic and random errors are of concern, the former particularly, because of the changes in technology and sampling methods over the many decades, the latter from the very great spatial and temporal variability. It remains possible that the database is insufficient to compute mean sea-level trends with the accuracy necessary to discuss the impact of global warming—as disappointing as this conclusion may be. The priority has to be to make such calculations possible in the future.

Establishing the credibility of satellite-borne altimetric sea-level measurements awaits the launch of NASA's new GRASP satellite or development of some other mechanism whereby the accuracy of geoid models can be improved.

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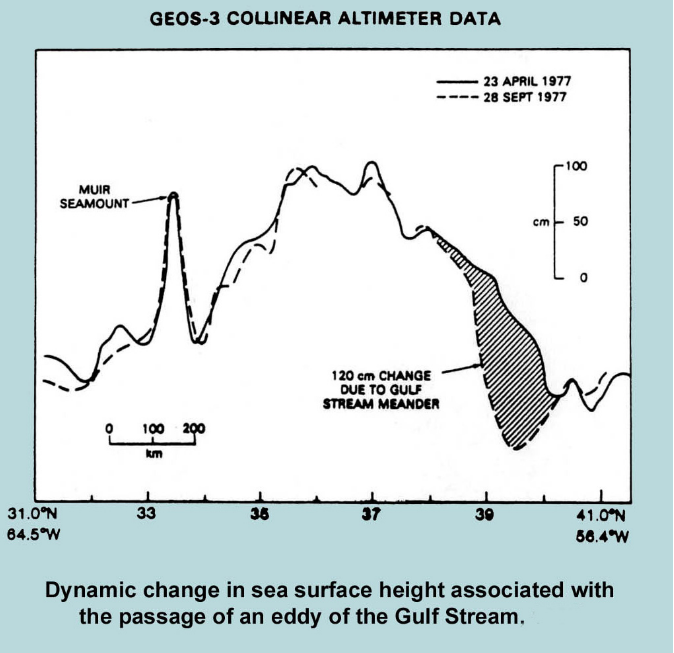
6.2.1.4. Short-term, decadal and multidecadal dynamic variability

Sea-level changes on a short-term, decadal, or multidecadal scale are driven by changes in the heat energy or dynamics of the ocean system (see, e.g., Figure 6.2.1.4.1; similar results were achieved by Fu *et al.*, 1987). These include the effects of spinning up or slowing down major current gyres and the effects of established climatic oscillations such as ENSO (El Niño-Southern Oscillation), the PDO (Pacific Decadal Oscillation), and the SAM (Southern Annular Mode). Sea-level change forced by such mechanisms is generally of low magnitude compared with geological time-scale changes (centimeters to a meter or two only) but can operate at rates as high as 5–10 mm/y.

Another important cause of shorter-term changes in sea level is fluctuation in the energy balance of the ocean, which leads to heating or cooling of the ocean; i.e., thermosteric sea-level change. Fluctuations in sea level have been linked to sunspot cycles (Currie, 1976) and longer-term solar effects (van der Schrier *et al.,*2002). After a phase of warming, expansion, and steric sea-level rise during the late twentieth century, ocean cooling has led to steric sea-level fall since 2002 (DiPuccio, 2009; Loehle, 2009).



Dynamic change in sea surface height associated with the passage of an eddy of the Gulf Stream.

Figure 6.2.1.4.1. Dynamic changes in sea surface height associated with the passing of an eddy of the warm water Gulf Stream, 1977. Adapted from Douglas, B.C., Cheney, R.E., and Agreen, R.W. 1983. Eddy energy of the Northwest Atlantic and Gulf of Mexico determined from GEOS 3 altimetry. *Journal of Geophysical Research: Oceans* **88**(C14): 9595–9603. doi:10.1029/JC088iC14p09595.

Kolker and Hameed (2007) have shown short-term, non-tidal, local sea-level variability is much greater than the magnitude of long-term trends. The cause of this variability is partly unknown, but it includes the effects of storms, winds, floods, wind-driven Rossby waves,[1] shifts in major ocean currents, volcanic heating, and meteorological phenomena (ENSO, PDO).

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[1] Oceanic Rossby waves travel from east to west under the influence of the shape and rotation of the Earth. They have dimensions of many hundreds of km horizontally but only displace the sea surface by a few cm. Nonetheless, Rossby waves transmit energy and redistribute momentum, thereby exerting effects on the intensity of ocean currents and affecting climate.

Earlier Research

Other papers that have identified short-term sea-level change signals include the following:

- Careful inspection of long historical tide gauge records identifies subtle decadal and multidecadal modulations on the twentieth century long-term rising trend (Marcos *et al.*, 2012). Twentieth century sea-level rise has imprinted on it a rhythmic pattern represented by successive periods of increasing and then decreasing rates of rise.
- In an analysis of high-quality tidal records selected worldwide, Holgate (2007) found a background average rate of sea-level rise of 1.6 mm/y (horizontal black line in Figure 6.2.1.4.2) with regular 20-year-long fluctuations of about -2 mm/y to +5 mm/y. Global sea level actually fell in the 1920s, 1940s, 1960s, 1980s, and around 2000.

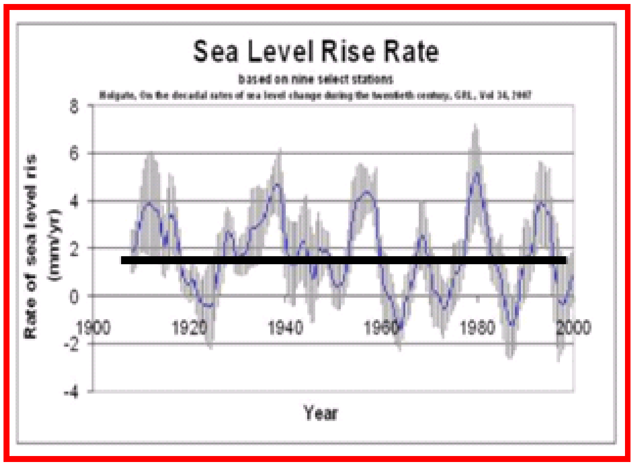

Figure 6.2.1.4.2. Rate of sea-level rise, 1910–2000, based upon analysis of high-quality tide gauge records. Note the average rate of rise (thick black line) of 1.6 mm/y. Note also the presence of fluctuations of rate of between about -2 and +5 mm/y on a decadal to multi-decadal scale, including periods of falling sea-level in 1920, 1940, 1960, 1980 and 2000. Adapted from Holgate, S. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

- Zhang and Church (2012) made a detailed study of interannual and decadal variability in Pacific Ocean sea-level trends. Noting "on a regional scale, such a signal [of anthropogenic change] is mixed with that due to natural climate variability," they set out to separate the natural and anthropogenic signals. This problem has become especially serious since the launch of the TOPEX/Poseidon altimeter, which has encouraged many researchers to report essentially meaningless linear trends in sea-level rise over time spans ranging from a ridiculously short three years to a still-inadequate 18 years.

Zhang and Church used continuous near-global altimeter measurements since 1993 to attempt to separate interannual and decadal sea-level variability in the Pacific from the long-term background sea-level trend. Their results show "the decreasing regional sea level in the eastern equatorial Pacific is mainly associated with the Pacific Decadal Oscillation" and "for those island countries in the western tropical Pacific and especially low-lying atolls, the high rate of sea level rise over the altimeter era has a significant component associated with natural variability." They conclude using altimeter-based trends as a reference for future climate change projections "needs to be treated with caution as regional sea level linear trends derived over the short altimeter era can be greatly affected by low-frequency climate variability."

Conclusions

Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and dictate the ocean response to atmospheric pressure. For environmental management purposes, the dominance of these processes means sea-level changes should be assessed at local or regional scales, not globally.

The presence of decadal and multidecadal fluctuations does not change the general conclusion from tide gauge data that sea level has been rising by an average of about 1.7 mm/year over the twentieth century. However, the presence of these oscillations has a significant effect on the usefulness of linear sea-level trends determined from datasets shorter than the 60-year period of one PDO cycle. Unless such trends are corrected to take into account the position the data they are based on occupies in the longer-term cycle, they are of little value for either scientific or environmental management purposes.

The pitfall is especially great when shorter periods of time are used to infer an acceleration of sea-level rise has occurred (e.g., Merrifield *et al.*, 2009; Sallenger *et al.*, 2012), because that acceleration might be due entirely to the fortuitous position within the 60-year cycle of the data studied (Chambers *et al.*, 2012). Chambers *et al.* state, "one should be cautious about computations of acceleration in sea level records unless they are longer than two cycles of the oscillation."

Natural decadal and multidecadal changes must be taken into account during any projection of future sea levels, yet it is only very recently that scientists have begun to incorporate such changes into their sea-level models.

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6.2.1.5. Acceleration of sea-level rise

Rates of sea-level change are periodic on decadal and longer time scales. For that reason, linear regression though eustatic data is an unreliable technique with which to establish long-term sea-level trends for use in environmental management. Accurate portrayal of any long-term ocean-heating (steric) sea-level rise, putatively due to human influence, is possible only after short-term periodic sea-level behavior has been identified and the records adjusted to account for it.

The important question is not, “is the long-term sea level rising?” Geological, tide gauge, and satellite records all agree it is and, other things being equal, will continue to do so. Instead, to ascertain if rates of sea-level rise are increasing due to human influence we should ask “is sea-level rise accelerating?” The answer to that question is no.

The IPCC (2001) wrote “no significant acceleration in the rate of sea-level rise during the 20th century has been detected.” In 2007 it noted “global average sea-level rose at an average rate of 1.8 [1.3–2.3] mm per year over 1961 to 2003. The rate was faster over 1993–2003: about 3.1 [2.4–3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear.” This interpretation was based on a comparison of satellite altimetry data, which started in 1991, and tide gauge data. As discussed above (6.2.1.3), the satellite data estimate a higher rate of sea-level rise than do tide gauge data (Wunsch *et al.,*2007), so this result is unsurprising and does not provide evidence of acceleration.

Subsequently, many authors have tested directly for accelerated rise using regional tide gauge datasets. For example, Hannah and Bell (2012) analyzed four 100-year long records from New Zealand’s four biggest ports (see Figure 6.2.1.5.1) and found no acceleration beyond the average linear rate of rise of 1.8 mm/yr.

Watson (2010) analyzed the three longest sea-level records (more than 100 years) available in Australasia, from Fremantle, Sydney, and Auckland. The average rates of sea-level rise exhibit by these sites since 1940 are 1.6, 0.4, and 1.2 mm/y, respectively, but all three sites show deceleration over the later parts of the twentieth century rather than acceleration (see Figure 6.2.1.5.2). Other authors also have provided evidence for a slowing rate of sea-level rise during the twentieth century, including Hannah (1990; 2004), Houston and Dean (2011, 2012), Boretti (2012a, b), and Gehrels *et al.* (2012). Woodworth *et al.* (2009) reviewed the available reconstructions for the twentieth century and concluded sea-level rise accelerated around 1920–1930 and decelerated around 1960.

Holgate and Woodworth (2004) derived a mean global, rather than regional, sea-level history using 177 coastal tide gauge records for 1955–1998. Extending that record back in time for another 50 years, Holgate (2007) analyzed nine long high-quality records from locations around the world (New York, Key West, San Diego, Balboa, Honolulu, Cascais, Newlyn, Trieste, and Auckland). The mean sea-level curve for these locations over the 1955–1998 period was compared with the mean curve of the much larger set of 177 stations to establish whether the mean nine-station record would provide a reasonable representation of global sea-level history for the longer period from 1904 to 2003. Holgate concluded, "a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to [do]."

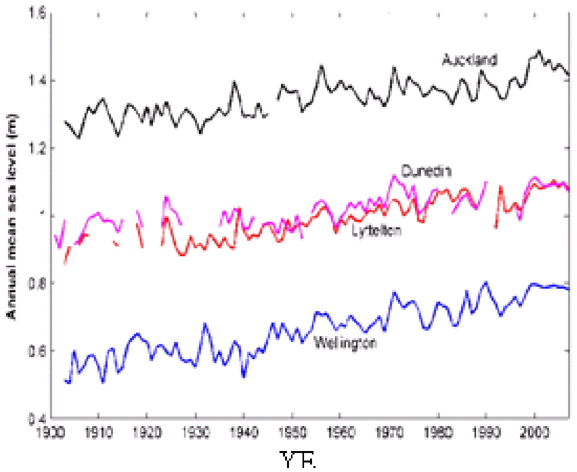

Figure 6.2.1.5.1. 100 year-long tide gauge records from four NZ ports (Auckland, Dunedin, Lyttleton and Wellington), showing a progressive, irregularly varying sea-level rise at an average background linear rate of 1.8 mm/yr. These rates of sea level change are similar to the world average rise as estimated from a global network of similar tide gauges. Adapted from Hannah, J. and Bell, R.G. 2012. Regional sea-level trends in New Zealand: *Journal of Geophysical Research* **117**: C01004–C01004.

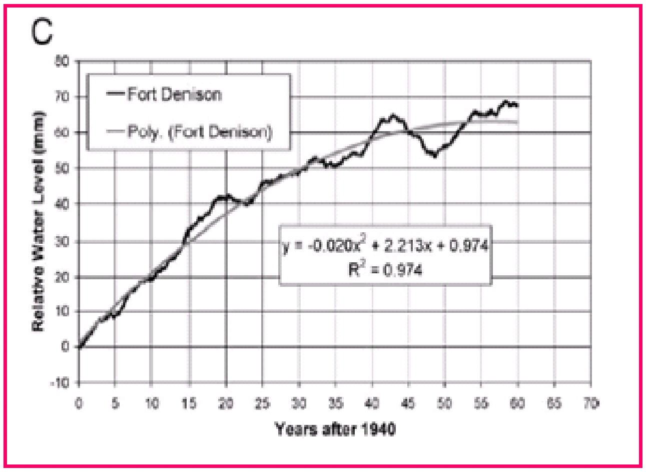

Figure 6.2.1.5.2. Sea-level curve for Sydney Harbour (Port Denison) since 1940, with fitted polynomial curve of decelerating nature. Adapted from Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea-level rise around mainland Australia? *Journal of Coastal Research* **27**: 368–377.

Holgate thereby was able to provide a best-estimate representation of the 1904–2003 mean global sea-level history of the world. This, like Jevrejeva *et al.*'s (2006) similar reconstruction based on a larger tide gauge dataset, showed both multidecadal variations and an overall declining trend (see Figure 6.2.1.5.3). He calculated the mean rate of global sea-level rise was "larger in the early part of the last century (2.03 ± 0.35 mm/year 1904–1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954–2003)." In other words, global sea-level rise has been decelerating since the mid-twentieth century.

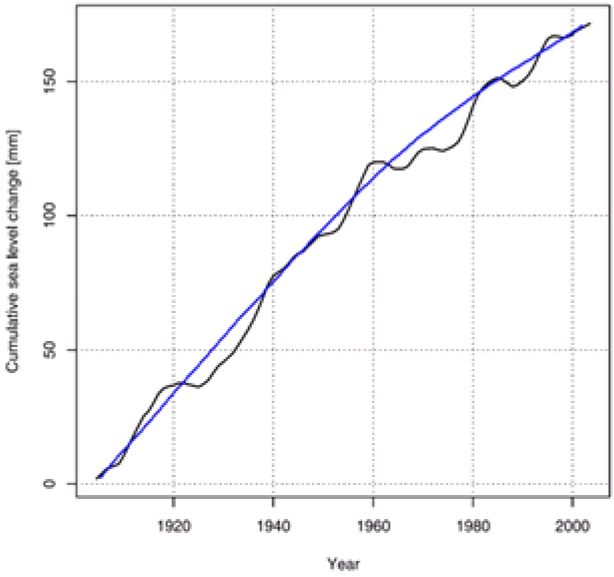

Figure 6.2.1.5.3. Cumulative increase in mean global sea level (1904-2003) derived from nine high-quality tide gauge records from around the world. Adapted from Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* **34**: L01602, doi: 10.1029/2006GL028492, 2007.

The only recent authors who claim to have detected recent acceleration in the rate of sea-level rise are Church and White (2006, 2011). Their earlier paper was based on merging short-term satellite altimetry with the long-term tide gauge records, a hazardous statistical exercise. The combined dataset was produced using a statistical model that matched adjusted tide gauge data and satellite measurements during the period of overlap, and then used that match to reconstruct past sea levels in an attempt to correct for the sparse spatial distribution of older tide gauge data. Church and White (2011) identify acceleration of the long-term sea-level record around 1930 followed by a deceleration around 1960. They also depict the short-term sea-level rise rate was faster at the end of the twentieth century than the long-term rate.

Only broad summaries of the Church and White (2006, 2011) methodologies have been published and their results should be looked upon with caution. Comparison between the earliest version and most recent version of their work indicate pre-satellite sea-level data change as additional satellite data become available. This occurs because the statistical model underlying the merging is changing with the addition of further overlapping data (Church and White, 2011). Furthermore, break point and other statistical analyses indicate a significant change in the underlying characteristics of the data around 1992 (Chambers *et al.,*2012), implying there was a fundamental change in sea-level processes then or the satellite data behave differently than the tide gauge data, as suggested by Wunsch *et al.* (2007) and Domingues *et al.* (2008). The presence of decadal and 60-year-long fluctuations in rates of sea-level change (Holgate, 2007; Chambers *et al.*2011) and brevity of the satellite altimetric record (6.2.1.3, above) suggest it is too soon to use the satellite data as a reliable test for acceleration in late twentieth century sea-level rise.

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Earlier Research

Several other recent papers bear on the question of an accelerated rate of sea-level rise and are briefly summarized below.

- Rahmstorf *et al.* (2012) compared Church and White (2006; 2011) and Jevrejeva *et al.* (2008) with three earlier reconstructions (Gornitz and Lebedeff 1987; Trupin and Wahr 1990; and Holgate and Woodworth 2004) of global sea level, finding general agreement among the analyses that sea-level rise began to accelerate in or before the nineteenth century (Jevrejeva, 2008), although there are very few tide gauge records extending back to the eighteenth century to better secure that result.

  The reconstructions used different sets of tide gauges and different methodologies, including different corrections applied to the data. These corrections include adjustments for local data shifts and corrections for the inverse barometric effect[2] and seasonal effects. Most importantly, the isostatic (GIA) corrections have changed over time as successively newer models of crustal deformation have been calculated, in which regard Houston and Dean (2012) found the predicted GIA was poorly correlated with the GIA measured by continuous GPS, with no systematic pattern of deviations. It should not be surprising there are significant differences as well as similarities between the datasets, and those differences will affect the detection of long-term changes in the rate of sea-level rise.

- Boretti (2012a) analyzed data from the TOPEX and Jason series of satellite radar altimeters to test for recent changes in the rate of sea-level change. He reports the average rate of sea-level rise over the almost 20-year period of radar altimeter observations is 3.164 mm/yr (see Figure 6.2.1.5.4), which if held steady over a century would yield a mean global SLR of 31.64 cm, a little more than the low estimate for 2100 made by the IPCC. Boretti also finds that rather than accelerating, the rate of sea-level rise over the measurement period is decelerating at a rate of -0.11637 mm/yr^2 and this deceleration is itself reducing at a rate of -0.078792 mm/yr^3.

  Boretti notes the deceleration of sea-level rise over the past ten years "is clearly the opposite of what is being predicted by the models," especially as the reduction has been even more pronounced over the past five years. He further notes, "in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the sea level rise must be almost 11 mm/year every year for the next 89 years." A rate of rise of 11 mm/yr has not been achieved once in the past 20 years; rates that fast have been experienced only during the full flush meltwater pulses during deglaciation. The average rise of 3.164 mm/yr found by Boretti is only 20 percent of the sea-level rise needed for the prediction of a one meter rise by 2100 to be correct.

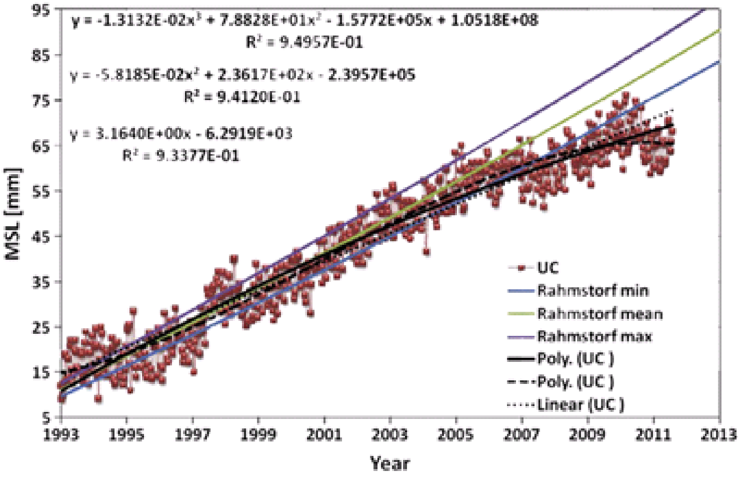

Figure 6.2.1.5.4. Comparison of MSL predictions from Rahmstorf (2007) with measurements from the TOPEX and Jason series. Boretti (2012a), who states in the figure caption that "the model predictions [of Rahmstorf, 2007] clearly do not agree with the experimental evidence in the short term." Adapted from Boretti, A.A. 2012a. Short term comparison of climate model predictions and satellite altimeter measurements of sea levels. *Coastal Engineering* **60**: 319–322.

- Boretti (2012b) reports the Australian government has said mass relocation of citizens will be required in the near future in response to "floods … due to the rise of sea levels resulting from increased carbon dioxide emissions." Government maps published for Sydney indicate 0.5, 0.8, and 1.1 meter rises in sea level. Boretti assesses the degree to which such alarm is justified and reports "the worldwide average tide gauge result obtained considering all the data included in the Permanent

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[2] In the open ocean, sea level tends to rise/fall 10 mm for every 1 hPa decrease/increase in atmospheric pressure. Because there are interannual and longer fluctuations in mean pressure at sea level, sea level fluctuates in parallel in response.

Service for Mean Sea Level data base show a modest sea level rise and about zero acceleration." He also notes "the Fort Denison, Sydney tide gauge result shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result."Similarly, "the Fremantle tide gauge result, the only other tide gauge operational in Australia over more than a century, shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result and the result of Sydney."Finally, he reports "the other tide gauges operational along the coastline of Australia over shorter time scales of 30 to 40 years on average also show the lack of any acceleration component in the rate of rise of sea levels."

Summarizing his findings, Boretti concludes the "rise of sea level in the bay of Sydney by 2100 is therefore more likely less than the 50 mm measured so far over the last 100 years, rather than the meter [1000 mm] predicted by some models."

- The Australian National Tidal Centre claimed 16 stations with 17 years of record showed a rate of sea-level rise of 5.4 mm/yr. Mörner and Parker (2013) reviewed the same records and found rates of sea-level rise average just 1.5 mm/yr, with no acceleration over recent years.

Conclusions

In its 2007 report, the IPCC projected global sea level was likely to rise somewhere between 18 and 59 cm by 2100. Since then, several model-based analyses have predicted much higher sea-level rise for the twenty-first century, even exceeding 1 meter in some cases (e.g., Rahmstorf, 2007; 2010).

In contrast, multiple careful analyses of tide gauge records by different research teams make it clear the acceleration of sea-level rise proposed by the IPCC and its scientists does not exist. Most records show either a steady state of rise or a deceleration during the twentieth century, both for individual records and for globally averaged datasets. In addition, and though only about 20 years long, the satellite radar altimeter dataset also records a recent decelerating rate of rise (Boretti, 2012a).

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6.2.1.6. Atolls

The assertion that Pacific coral islands are being swamped or "drowned" by rising sea level, thus creating thousands of "climate refugees," retains its hold over many environmentalists, although a London High Court judgment in 2007 against Al Gore found the claim to be untrue (Burton, 2007). Relentless media attention to the matter has ensured it remains in the public eye, with the Tuvalu Islands (Funafuti) receiving the most attention.

Charles Darwin was the originator of the modern theory of coral island and atoll formation (Darwin, 1842) (see Figure 6.2.1.6.1). He speculated when a new volcano erupts above sea level in the tropical

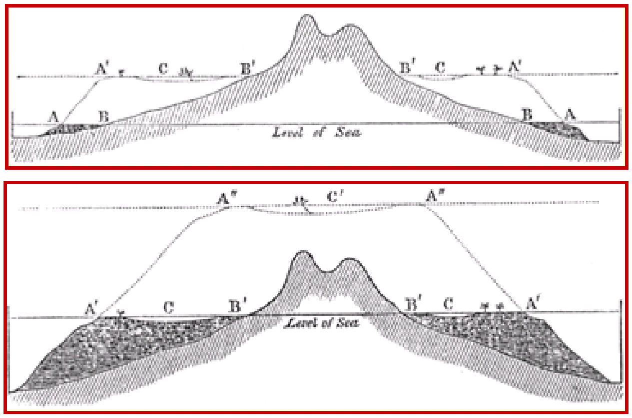

Figure 6.2.1.6.1. The formation of atolls by coral growth around a sinking volcanic island. Adapted from Darwin, C. 1842. *The Structure and Distribution of Coral Reefs.* London, Smith, Elderand Co.

ocean, corals colonize the shoreline, taking the form of fringing reefs. As the volcano cools and subsides, the reefs grow upwards and outwards, away from the volcanic island, keeping pace with the local sea-level rise caused by subsidence. A shallow-water lagoon forms between the island and the living reef, comprising an offshore, perimeter barrier reef. In the final stage of subsidence, the island itself disappears below sea level to leave a ring of coral reef that marks the location of the sunken volcano; thus are atolls born.

Seldom more than a meter or two above sea level, all atolls and related sand-cay and gravel-motu islands are at the continuing mercy of the wind, waves, tides, and weather events that built them. They are dynamic features of the seascape; over timescales of decades to centuries they erode here, grow there, and sometimes disappear beneath the waves forever. A coral atoll is not so much a "thing" as a process, and they are obviously not good places on which to develop major human population centers.

Because they are located so close to sea level, it is commonly assumed atolls or coral sand/gravel islands (cays or motu) are vulnerable to rising sea level. But investigations into the processes that govern the formation, evolution, and stability of cays and motu indicate they are very resilient to sea-level changes, provided human activities do not disrupt the natural processes, such as by constructing sea walls (Perry *et al.*, 2011). Formation of cays and motu requires sufficient sediment supply and sufficient wave energy acting on the reef surface to transport and deposit sediment. Perhaps counterintuitively, overwashing of the islands by storm waves, storm surges, perigean tides, and tsunami is an important mechanism for increasing the elevation of the island by depositing new layers of sediment (Baines and McLean, 1976; Kench and Brander, 2006; Woodroffe, 2008; Etienne and Terry, 2012). When sea level rises, corals grow up to the higher sea level, normally easily keeping pace even at high rates of sea-level rise. When sea-level rise stops, the coral can grow only sideways.

Hence atolls are not a fixed "dipstick" with which to measure sea-level rise, as they are often treated: rather, a living coral reef forms part of a greater dynamic natural system. As Webb and Knetch (2010) write, "Typically, these [alarmist] studies treat islands as static landforms," but "such approaches have not incorporated a full appreciation of the contemporary morphodynamics of landforms nor considered the style and magnitude of changes that may be expected in the future. Reef islands are dynamic landforms that are able to reorganize their sediment reservoir in response to changing boundary conditions (wind, waves and sea-level)." Coral growth, erosion, transport, and deposition of sediment and the prevailing oceanography and meteorology must be taken into account. The very fact that we have so many coral islands in the world, despite a rise in sea level of more than 100 m since the last ice age, shows coral islands are resilient—they don't drown easily.

In essence, there appears to be an accommodation space, centered on mean sea level, that provides both the sediment and the energy needed to initiate and sustain coral cays and motu. Provided sea-level changes are slower than the rate at which the system can adjust the accommodation space, cays and motu are sustained. Rates of sea-level change for the foreseeable future are not high enough to threaten islands that are free to adjust in this way.

Connell (2003) found no evidence for the oft-repeated island doomsday claims about Tuvalu. Yamano *et al.* (2007) assessed 108 years of data for Fongafale Islet, Tuvalu, and found the problems attributed to sea-level rise in fact were due to population pressures resulting in the occupation of swamp land subject to periodic flooding throughout the historical record, thus demonstrating the great importance of real-world data—as opposed to climate model simulations—when it comes to considering the current and future status of Earth's many low-lying islands. As Yamano *et al.* (2007) state, "examinations of global environmental issues should focus on characteristics specific to the region of interest. These characteristics should be specified using historical reconstruction to understand and address the vulnerability of an area to global environmental changes.”

Webb and Kench (2010) found during the last part of the twentieth century 23 of the 27 Pacific atolls they studied remained unchanged or increased in area. They conclude, “The results show that island area has remained largely stable or increased over the time frame of analysis. Forty-three percent of islands increased in area by more than 3% with the largest increases of 30% on Betio (Tarawa atoll) and 28.3% on Funamanu (Funafuti atoll).” Over time, the island shapes changed in response to variations in dominant wave direction, and some islands migrated over their adjacent reef surfaces. A sensible management approach to this dynamic problem would be to design infrastructure so it can migrate with the evolving island, rather than attempt to maintain the island “frozen” in some arbitrary historical configuration.

In addition to the positive feedback loop of increased sediment supply demonstrated by Webb and Kench, the available evidence suggests the rate of long-term sea-level rise for most Pacific coral islands is less than the current global average rate of rise (see Figure 6.2.1.6.2). These records begin in 1993, when the Australian government set up a new series of accurate tide gauges to measure sea-level change on 14 tropical Pacific islands. At 19 years’ duration, even the longest of the records is too short to provide accurate long-term trend signals that might be associated with global warming. As the authors point out, “Caution must be exercised in interpreting the short-term trends—they will almost certainly change over the coming years as the dataset increases in length.”

No data exist to demonstrate an increasing, unusual, or unnatural rate of sea-level change for Pacific atolls, let alone any direct influence from increasing atmospheric carbon dioxide. As Meyssignac *et al.* (2012) conclude, “Results suggest that in the tropical Pacific, sea level trend fluctuations are dominated by the internal variability of the ocean-atmosphere coupled system. While our analysis cannot rule out any influence of anthropogenic forcing, it concludes that the latter effect in that particular region is still hardly detectable.”

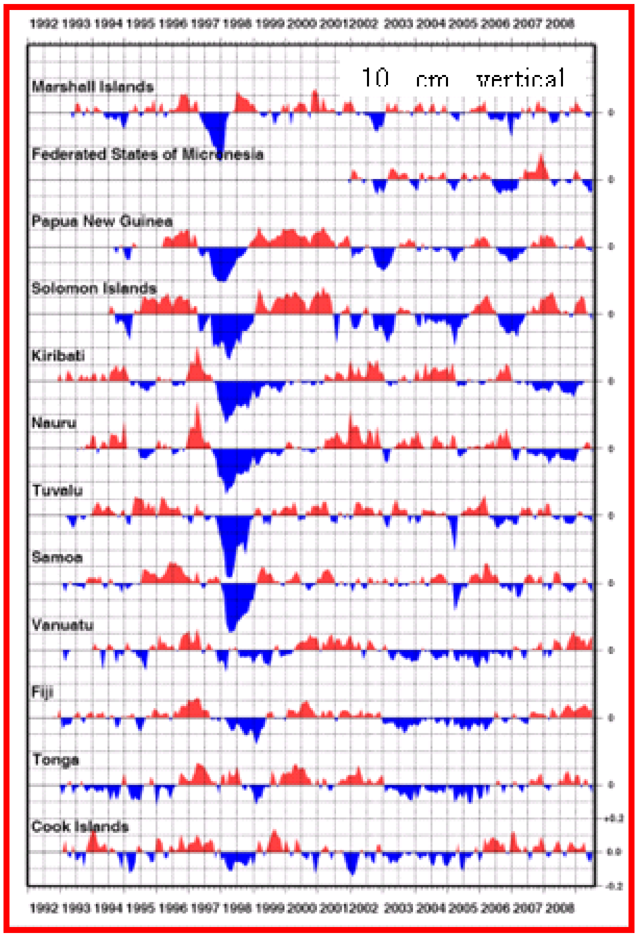

Figure 6.2.1.6.2. Relative sea-level variations since 1992, Pacific Island network. Australian Bureau of Meteorology, 2011. The South Pacific Sea-level and Climate Monitoring Program. Sea-level summary data report, July 2010–June 2010. http://www.bom.gov.au/ntc/IDO60102/IDO60102.2011_1.pdf.

Conclusion

The dynamic nature of an atoll is exacerbated, and its integrity jeopardized, when it is subjected to the environmental pressures created by a growing human population. Sand mining, construction project loading, and rapid groundwater withdrawal all cause local lowering of the ground surface, thereby encouraging marine incursion quite irrespective of any sea-level change. It is these processes in combination with episodic natural hazards such as tides and storms, not global sea-level change, that provide the alarming video footage of marine flooding on Pacific Islands that from time to time appears on our television news.

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Earlier Research

Other recent papers on the effects of sea-level change on atolls or coral reefs are summarized below.

- Kench *et al.* (2005) proposed a new model for reef-island formation based on work conducted at the Maldives in the Indian Ocean. The model indicates island formation starts below sea level with the accumulation of sand and gravel bars. Once these catch up with sea level and emerge, the calcareous sediment is stabilized by vegetation and lithification (beach rock formation). Subsequently the growth of the island is determined by the supply of sediment through overwashing processes.
- McCoy *et al.* (2010) examined the Mamanuca Islands, Fiji, and found that although the islands were younger than the Maldives, the same model was valid. They conclude "contemporary development of the reef islands in the Mamanuca's and their links to sediment production on the reef flat suggests that they may be able to adjust their morphology to future environmental conditions."
- In a study of Raine Island (11°35'28"S, 144°02'17"E), outer Great Barrier Reef (Australia), Dawson and Smithers (2010) employed historic survey maps, topographic survey datasets of earlier researchers, and modern digital elevation data to reconstruct a 40-year (1967–2007) shoreline history of the island. Their analyses demonstrated Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007, and overall Raine Island underwent a net accretion of 68,400 ± 6,700 m^3 during that time. Dawson and Smithers conclude "future management strategies of Raine Island and other islands of the Great Barrier Reef should recognize that perceptions of reef island erosion can arise from large short-term seasonal and storm-derived sediment redistribution from one part of the island to another or to a temporary storage on the adjacent reef flat" but these phenomena do not necessarily lead to "a net permanent loss from the island sediment budget."
- Rankey (2011) based his integrated study of 17 islands on the Maiana and Aranuka atolls of Kiribati's Gilbert Island chain on integrated field observations, differential global positioning system data, historical aerial photographs, and ultrahigh-resolution remote sensing images. Examining the nature, spatial patterns, and rates of change of the shorelines of the islands he studied, Rankey found short-term (four-year) rates of shoreline change can indeed be dramatic, with significant intrusion of seawater over shallowly sloping shores. Over longer (40-year) periods the rates of change are much smaller and result in both slightly larger (growing) and slightly smaller (shrinking) islands. Rankey concludes "the atoll islands are not washing away" and counsels "solutions must consider the natural complexity of these [island] systems, rather than advocate overly

simplistic notions of the causes of, and the solutions to, coastal change."

- Ford (2012) reported on the shoreline status of Majuro Atoll, the capital and most populated atoll in the Republic of the Marshall Islands. He used a combination of aerial photos and satellite imagery to analyze shoreline change of the island over the past three-and-a-half decades, a period characterized by rapidly increasing population, coastal development, and a rising sea level on the order of 3 mm/year. Although the rural lagoon shore of Majuro Atoll has been predominantly eroding, Ford found, the ocean-facing shore has been largely accreting, and at a much faster rate. Within the urban area of Majuro he finds shoreline change "has been largely driven by widespread reclamation for a mix of residential, commercial and industrial activities." Thus, "despite a rising sea level … the landmass of Majuro has persisted and, largely because of reclamation, increased in size." Ford notes demands are placed on the limited land available as an atoll population increases, but for Majuro Atoll "it is likely that land reclamation will continue to satisfy this demand." He adds, "the notion that sea level rise is a singular driver of shoreline change along atolls is spurious," and "adopting such a notion is an impediment to the sustainable management of coastal resources within urban atolls."
- Dunne *et al.* (2012) studied rising sea levels around the shorelines of the Chagos Archipelago (which includes the Diego Garcia Atoll), Indian Ocean. Sheppard and Spalding (2003) had reported a tide gauge situated on Diego Garcia indicated a local sea-level rise of 5.44 mm/year for 1988–1999. Just three years later, another analysis of the same gauge for the slightly longer period 1988–2000 had reported a lesser rate of 4.35 mm/year (Ragoonaden, 2006). In Dunne *et al.*'s view both of these analyses "were based only on short tide-gauge datasets, involved inappropriate statistical methods, and as a result have given an erroneous impression of the magnitude and significance of sea-level rise in this area."

Dunne *et al.* used tide gauge and satellite altimeter records and ocean models and found "no evidence of any statistically significant sea-level rise either from the Diego Garcia tide gauge (1988–2000 and 2003–2011) or in the satellite altimetry record (1993–2011)." In addition, they note the lack of evidence for subsidence in the islands, consistent with GPS observations that Diego Garcia uplifted by 0.63 ± 0.28 mm/year between 1996 and 2009. Dunne *et al.* conclude, "collectively these results suggest that this has been a relatively stable physical environment, and that these low-lying coral islands should continue to be able to support human habitation, as they have done for much of the last 200 years."

Conclusions

On October 17, 2009, members of the Maldives' Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to the very existence of their country's nearly 1,200 coral islands. While underwater, they signed a document calling on all nations to reduce carbon (sic) emissions in response to the carbon dioxide threat.

The papers summarized above make it clear that observational and field evidence from a wide geographic range of low-lying ocean islands directly contradicts this theoretical threat.

Studies such as those by Webb and Kench (2010) and Dawson and Smithers (2010) have enabled a much better understanding of the likely effects of sea-level rise, should it happen, on low-lying islands. These effects include an increasing accommodation space for new coral reef growth and (bioclastic) sediment; reinvigoration of carbonate production on reef flats where further vertical reef growth today is inhibited by a stable or falling sea level; and an increase in the efficiency of waves to transport and accrete new and stored sediment to an island depocentre. The views of the Maldives Cabinet and its supporters notwithstanding, a rise in sea level on coral shorelines will most likely lead to an expansion of reef area and associated sediment banks. As Webb and Kench concluded, in contradiction of "widespread perceptions that all reef islands are eroding in response to recent sea level rise, … reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20–60 years."

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6.2.1.7. Other sea-level studies

We summarize in this section three recent sea-level studies that are not easily categorized.

- Woppelmann *et al.* (2008) examined "the issue of a possible tide gauge datum discontinuity for Brest … caused by the bombing of the city in August 1944," using historical leveling information and a comparison of sea-level data between adjacent stations. The Brest tide gauge was found to be "'stable' over the 1889–1996 period" because of the development of "an accurate datum connection between recently rediscovered 18th century sea level data (back to 1711) and those of the present day." An "interesting by-product" of their analysis was the close match that emerged between the Brest record and two long tide records in the U.K. at Liverpool and Newlyn. The three records show a roughly coincident increase in the rate of relative sea-level rise around the end of the nineteenth century, after which all three datasets define similar linear increases with time through to 2007.

If one splits the period of linear sea-level rise determined for Brest into two equal 57-year parts centered on the middle of the twentieth century—1893 to 1950 and 1950 to 2007—the two parts can be compared with an atmospheric CO_2 concentration that rose about 3.8 times faster over the second period than it did over the first. Since mean sea level rose at a constant rate over the entire 114 years, it is unlikely the historical increase in atmospheric CO_2 controlled the steady sea-level rise.

- Langley *et al.* (2009) studied the effect of rising sea level on coastal wetlands in the eastern United States with respect to plant growth and CO_2 concentration. In the microtidal Kirkpatrick Marsh of Chesapeake Bay, each of several 200m^2 plots was outfitted with a surface elevation table (SET) to measure soil elevation change. Langley *et al.* then exposed half the plots to an extra 340 ppm of CO_2 for two years, while "data from a greenhouse mesocosm experiment (Cherry *et al.*, 2009) were used to examine how elevated CO_2 might affect elevation response under simulated sea level rise scenarios."

The researchers found the plots with extra CO_2 increased fine root productivity by an average of 36 percent over the two-year study, and aboveground biomass production was increased by as much as 30 percent. These results were consistent with a 20-year record of elevated CO_2 treatment in a previous study on the same marsh by Erickson *et al.* (2007). The elevated CO_2 also caused an increase in root zone thickness of 4.9 mm/year compared with only 0.7 mm/year in the ambient CO_2 treatment, resulting in "a slight loss of elevation in ambient CO_2 (-0.9 mm/year) compared with an elevation gain (3.0 mm/year) in the elevated CO_2 treatment." Furthermore, Cherry *et al.* (2009) have determined from another greenhouse mesocosm experiment that "the CO_2 effect was enhanced under salinity and flooding conditions likely to accompany future sea level rise."

Langley *et al.* conclude, "by stimulating biogenic contributions to marsh elevation, increases in the greenhouse gas, CO_2, may paradoxically aid some coastal wetlands in counterbalancing rising seas." They note this finding bears "particular importance given the threat of accelerating SLR to coastal wetlands worldwide," such as the recent Environmental Protection Agency report of Reed *et al.* (2008), which suggested "a 2-mm increase in the rate of SLR will threaten or eliminate a large portion of mid-Atlantic marshes." Langley *et al.*'s research suggests the growth-promoting effect of atmospheric CO_2 enrichment will more than compensate for its hypothetical sea-level-raising effect.

- Albrecht *et al.* (2011) developed an index time series for changes in regional mean sea-level (RMSL) changes in the German Bight, North Sea. They employed two approaches—one that uses arithmetic means based on all available data for each time step, and another that uses empirical orthogonal functions. For comparison of their results with global mean sea-level data they used the 15 tide gauge dataset for 1843–2008 described and provided by Wahl *et al.* (2010, 2011).

Albrecht *et al.* report both methods produce similar results for the time period 1924–2008. Regional mean sea level increased at rates between 1.64 and 1.74 mm/year with a 90% confidence range of 0.28 mm/year in each case. Regarding possible acceleration in RMSL rise within the past few decades, they note in terms of 20-year trends, the most recent rates are "relatively high … but not unusual and ... similar rates could also be identified earlier in the record." Albrecht *et al.* reaffirm in the conclusion of their paper that "present rates of RMSL rise in the German Bight are relatively high, but are not unusual in the context of historical changes." Similar conclusions regarding recent acceleration were drawn by Haigh *et al.* (2009) for the North Sea region of the English Channel.

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6.2.1.8. Isostasy, GRACE

6.2.1.8.1 Isostasy

The reconstructed post-glacial sea-level curve of Figure 6.2.1.8.1.1 attempts to portray the true eustatic sea-level history of the past 20,000 years. To a first approximation, it is a history of the increasing volume of water in the world ocean caused by glacial melting and the steric expansion of a warming ocean. However, the measurements that underpin curves like this are made with respect to particular local relative sea levels at specific coastal locations and are affected by the movement up or down of the local geological substrate as well as by the notional global sea level.

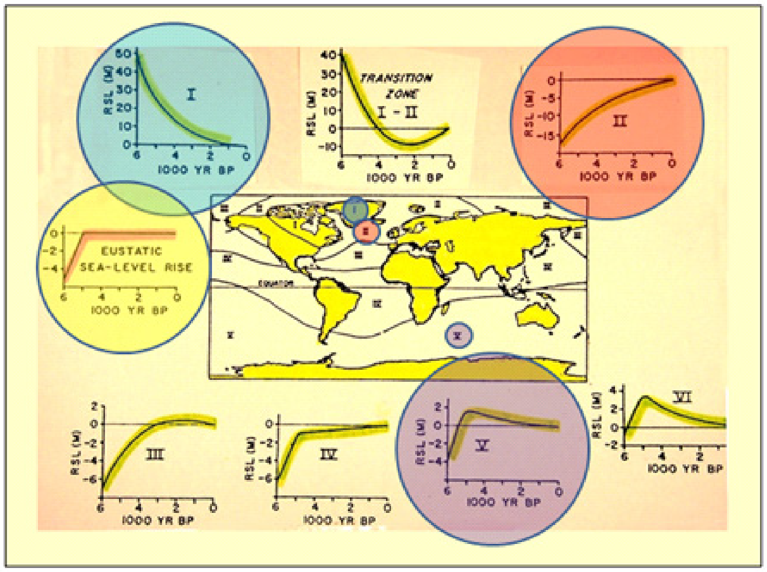

Figure 6.2.1.8.1.1. Local relative sea-level curves for the past 6,000 years, modeled to include hydro-isostatic effects combined with an idealized eustatic curve. Adapted from Clark, J.A. and Lingle, C.S. 1979. Predicted relative sea-level changes (18,000 Years B.P. to present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research* **11**: 279–298.

As the ice melted after the last glaciation, the increasing volume of the ocean caused two important changes to occur in the surface loading of Earth. First, the removal of an ice cap causes the formerly depressed (by loading) crust beneath to rebound upward by glacio-isostasy. Over 10,000 years during the Holocene, this rebound attained a magnitude of more than 100 meters at locations beneath the center of the former Scandinavian icecap, which are therefore characterized by falling post-glacial sea levels.

Second, an increasing ocean volume causes sea level to rise and the shoreline to transgress across the edges of the continental platforms, turning former glacial coastal plains into today's shallowly submergent continental shelf. The extra ocean water above the flooded continental shelf has the form of a coastline-parallel, landward-tapering prism, which provides a new crustal load that subsequently causes gentle hydro-isostatic uplift in the vicinity of the shoreline and hydro-isostatic sinking offshore, in both cases with a magnitude up to a few meters.

Overall, the effect is one of a seaward tilting of the crust beneath the continental shelf, with the rotational axis of tilting located near the sea-level high-stand shoreline (Chappell *et al.*, 1983; Tamisiea and Mitrovica, 2011).

In a classic 1979 paper, Clark and Lingle provided a modeled analysis of the way in which these isostatic effects combine with an assumed eustatic sea-level curve (see Figure 6.2.1.8.1.1, yellow circle) to produce a variety of local sea-level responses over the past 6,000 years that can be organized into recognizable geographic zones.

In proximal locations beneath former icecaps such as Greenland (blue circle; Zone I), strong glacio-isostatic rebound produces a falling relative sea-level. In far-field locations such as Australia and New Zealand (purple circle; Zone V), a shoreline overshoot of 2–4 meters at the end of the eustatic rise is followed by gradual relative sea-level fall in response to gentle hydro-isostatic deformation. And in intermediate locations such as the margins of the North Atlantic Ocean (red circle; Zone II), situated on the periphery of ice-sheet loading influence, interaction of these and other factors results in a relative sea-level curve that rises asymptotically to the present shoreline.

Isostatic uplift at a rate of, say, 2 mm/y (20 cm/century) may not sound like much on human generational time scales, but if the change is negative (land sinking) it is enough to more than double the "best estimate" 18 cm/century rate of global sea-level rise over the twentieth century. Conversely, if the change is positive (land rising), it is enough to convert that same eustatic rise into a falling rate of 2 cm/century. Obviously, and as Clark and Lingle were among the first to model, over geological timescales of millennia even small rates of isostatic depression or rebound can have a significant effect on the physiography of the shoreline and its position relative to local sea level.

The effect of these isostatic effects is displayed in Figure 6.2.1.8.1.2, which is a plot of the present-day elevations of more than 4,000 worldwide radiocarbon-dated shorelines of post-glacial age. Predictably, the pattern displayed is one of increasing elevation of particular shorelines above or below sea level with increasing time elapsed (i.e., from left to right across the figure), the sign of any plotted point indicating whether the sampled site is in an area of uplift or sinking. Accordingly, sites situated around sea level at 10,000 y BP (early Holocene) now occupy a range of elevations between about -100 m and +150 m, which indicates subsidence and uplift rates of up to -10 mm/y and +15 mm/y, respectively.

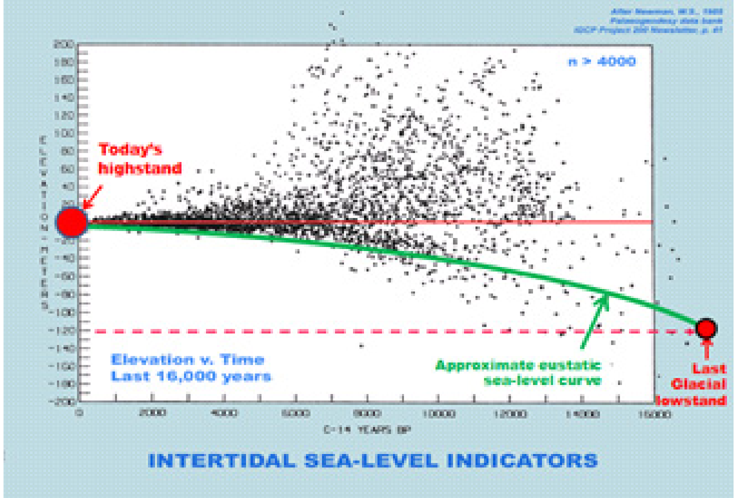

Figure 6.2.1.8.1.2. Worldwide plot of shoreline elevations with ages between 16,000 yBP and today. Adapted from Pirazzoli, P.A., Grant, D.R,. and Woodworth, P. 1989. Trends of relative sea-level change: past, present and future. *Quaternary International* **2**: 63–71. doi:10.1016/ 1040-6182(89)90022-0.

The large changes in ground level caused by glacio- and hydro-isostasy in the short period since the last glaciation serve as a warning regarding the naïve application of paleo-sea-level data from the previous interglacial, about 125,000 years ago. Sea-level indicators from the last interglacial also may be distorted by differing regional isostatic responses, but over about 100,000 rather than 15,000 years. It is thus inadvisable to use such data as predictors of future maximum sea levels during the present interglacial (Holocene and Recent).

The difficulty arises not only because of GIA variability in time and space, but also from longer-term uplift or depression in different tectonic provinces. Means of separating the sea-level and tectonic influences have been devised (Chappell, 1974), but they rely on assumptions of a fixed sea-level point in time. Even in locations thought to be unaffected by major crustal uplift or depression, geochronological ages suggest successive sea levels reached much the same elevation (van Vliet Lanoe *et al.*, 2000). Claims of a last interglacial sea level of between +6.6 and +9.4 m from a probabilistic analysis along allegedly stable coastline areas (Kopp *et al.*, 2009) contain circular arguments. In any event, what constitutes a stable region and how can such stability be shown? In addition, other crustal influences are usually ignored; Menard (1971) provided a map of oceanic crust, created since the last interglacial at mid-ocean ridge, that would have displaced sea level. The similar effects stemming from subduction zone changes have, to our knowledge, never been quantified.

Conclusions

IPCC commentary regarding sea level centers strongly on the calculation and manipulation of changes in the theoretical global average. But realistic management of sea level and other environmental issues cannot be undertaken at a global level, but rather must acknowledge the many and varied ways in which geological anisotropy imposes its signature at local and regional scales. Isostatic change—which is influenced by such factors as water and ice loading, rates of seafloor spreading and subduction, and even phase changes in the upper mantle—imposes an inescapable uncertainty on predictions of future climate-related sea-level change. Such change will be regionally variable and mostly of small magnitude over centennial time scales.

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6.2.1.8.2. GRACE

The conversion of satellite radar altimeter measurements into an accurate measure of the sea-surface level requires an accurate knowledge of both ocean mass and the shape of Earth, yet Earth's shape is constantly changing because of isostatic adjustments. Earth's shape is conventionally modeled as the geoid, which over the oceans is defined as the equipotential surface of Earth's gravity field that best fits, in a least squares sense, global mean sea level. One of the major difficulties of measuring sea-level changes from space is immediately apparent: The reference level is itself a function of the parameter being measured.

In 2002, twin orbiting satellites—the Gravity Recovery and Climate Experiment (GRACE)—were launched to provide better estimates of the ocean mass component of the sea-level budget. Although in principle the data provided by GRACE could lead to the accurate reconstruction of sea levels, the complex operational corrections that must be applied to spaceborne geophysical datasets mean "at best, the determination and attribution [in this way] of global-mean sea level change lies at the very edge of knowledge and technology" (Wunsch *et al.*, 2007).

Part of the processing of GRACE data is its correction in terms of an assumed model for glacial isostatic adjustment (GIA). Disappointingly, data from the GRACE satellites have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and others.

NASA's Jet Propulsion Laboratory (JPL) recently has acknowledged the importance of solving this problem by announcing a $100 million mission to launch a Geodetic Reference Antenna in Space (GRASP) satellite to improve the measurement of the TRF (geoid) used to calculate satellite sea-level measurements (NASA JPL, 2012). JPL acknowledges the current lack of an accurate model of Earth's reference frame has introduced spurious (and unknowable) errors into all satellite-borne sea-level, gravity, and polar ice cap volume measurements (Bar-Sever *et al.*, 2009).

A detailed analysis of processing and post-processing factors affecting GRACE estimates of ocean mass trends is provided by Quinn and Ponte (2010), who compare results from different GRACE data centers and explore a range of post-processing filtering and modeling parameters, including the effects of geocenter motion, postglacial isostatic rebound, and atmospheric pressure. Quinn and Ponte report the mean ocean mass trends they calculated "vary quite dramatically depending on which GRACE product is used, which adjustments are applied, and how the data are processed. For example, the isostatic rebound adjustment ranges from 1 to 2 mm/year, the geocenter adjustment may have biases on the order of 0.2 mm/year, and the atmospheric mass correction may have errors of up to 0.1 mm/year," with differences between GRACE data centers also being large, up to 1 mm/year.

Despite the inherent uncertainty of the results, GRACE satellite data have been used in several studies to estimate sea-level rise due to global warming. The particularly confounding factor in these studies is that continental edges and ocean basins respond to past and recent mass loss or additions by rising or sinking (Gehrels, 2010). Thus a falling sea level could reflect glacial isostatic rebound at the same time the actual worldwide trend was one of increasing ocean mass and consequent sea-level rise; and vice versa.

Leuliette and Miller (2009) assert "Global mean sea level change results from two major processes that alter the total volume of the ocean," and thus its mass. These processes are changes in total heat content and salinity, which produce density or steric changes; and the exchange of water between the oceans and other reservoirs, such as glaciers, icecaps, and land-based liquid water reservoirs. Although satellite radar altimeters have been providing data since the early 1990s, it is only since 2002 (GRACE) that global gravity estimates of mass variation have been available, and not until 2007 were accurate measurements made of global steric change (Argo ocean-profiling floats). It is probably for these reasons that prior attempts to close the global sea-level budget (Lombard *et al.*, 2007; Willis *et al.*, 2008) were unsuccessful.

Leuliette and Miller attempted a new analysis of the sea-level-rise budget for the period January 2004 to December 2007 using corrected Jason-1 and ENVISAT altimetric measurements, improved upper ocean steric data from the Argo array, and ocean mass variations calculated from GRACE gravity observations. The improved datasets closed the global sea-level-rise budget and indicated the sum of global steric sea level and ocean mass components had a trend of 1.5 ± 1.0 mm/year over the period of analysis. This result agrees with the measurements made by the Jason-1 (2.4 ± 1.1 mm/year) and ENVISAT (2.7 ± 1.5 mm/year) satellites within the 95% confidence interval.

Noting the last of these three results is 80 percent greater than the first, the question remains as to which result lies closest to the truth. Since Woppelmann *et al.* (2009) recently obtained a result of 1.58 ± 0.03 mm/year by analyzing GPS observations from a global network of 227 stations for the period 1997–2006, and given that both Church and White (2006) and Holgate (2007) obtained a result of 1.7 mm/year, it appears likely Leuliette and Miller (2009) have provided the most accurate result yet of any of the satellite altimeter studies.

Ivins *et al.* (2013) recalculated the contribution of Antarctic melt to sea-level rise using a claimed improved GIA correction. The GRACE data between January 2003 and January 2012, uncorrected for GIA, yield an ice mass rate of +2.9 ± 29 Gt/yr. The new GIA correction increases the solved-for ice mass imbalance of Antarctica to -57 ± 34 Gt/yr. The revised GIA correction is smaller than past GRACE estimates by about 50 to 90 Gt/yr, leading to a new upper bound to sea-level rise from Antarctic melt over the averaged years about 0.16 ± 0.09 mm/yr.

Baur *et al.* (2013) used GRACE data to assess continental mass variations on a global scale, including both land-ice and land-water contributions, for 19 continental areas that exhibited significant signals. This was accomplished for the nine-year period 2002–2011 using the GIA model of Paulson *et al.* (2007) to remove the effects of isostatic adjustment. In contrast to previous authors, Baur *et al.* stress "present-day continental mass variation as observed by space gravimetry reveals secular mass decline and accumulation," and "whereas the former contributes to sea-level rise, the latter results in sea-level fall." Reliable overall estimates of sea-level change must consider mass accumulation, rather than solely mass loss. Baur *et al.* report the mean mass gain and mass loss in their 19 primary areas was -0.7 ± 0.4 mm/year of sea-level fall and +1.8 ± 0.6 mm/year of sea-level rise, for a net effect of +1.1 ± 0.6 mm/year. To obtain a figure for total sea-level change, a steric component of +0.5 ± 0.5 mm/year (after Leuliette and Willis; 2011) was added, yielding a final uncorrected result of +1.6 ± 0.8 mm/year or a geocenter-corrected result of +1.7 ± 0.8) mm/year. These results are telling because the inferred rates of rise correspond almost exactly with the best- available independent measurements made with tide gauges (e.g., Church and White, 2006; Holgate, 2007).

Conclusions

Tide gauge reconstructions (Church and White, 2006) have found the rate of sea-level rise over the past century has been only 1.7 ± 0.5 mm/year. It seems strange to question this result using a GRACE-derived assessment with its many and potentially large errors and biases. Among other concerns, "non-ocean signals, such as in the Indian Ocean due to the 2004 Sumatran-Andean earthquake, and near Greenland and West Antarctica due to land signal leakage, can also corrupt the ocean trend estimates" (Quinn and Ponte, 2010).

Despite these problems, the latest GRACE estimates of Baur *et al.* (2012) correspond closely with their counterpart tide gauge estimates. Nonetheless, the GRACE satellites must develop a much longer history of satisfactory data acquisition before they can be considered a reliable means of providing accurate assessments of ocean mass and sea-level change. As Ramillien *et al.* (2006) have noted, "the GRACE data time series is still very short," so any results obtained from it "must be considered as preliminary since we cannot exclude that apparent trends [derived from it] only reflect inter-annual fluctuations."

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6.2.1.9. Computer modeling

Graphs projecting future sea level can be constructed in three ways: empirical, semi-empirical, and deterministic modeling. Papers using these techniques are referred to in many other places in this chapter; here we discuss the modeling techniques themselves.

6.2.1.9.1 Empirical models

An empirical model is constructed by plotting a series of mean sea-level measurements against time and then summarizing any trend present by fitting a statistical model, usually the best-fit straight line, to the ensemble of points (e.g., Figure 6.2.1.3.3 above). Extrapolation of the assumed relationship can be used to project future sea-level positions. These techniques fit a statistical relationship to existing data in order to provide some basis for extrapolation beyond the period of the dataset; importantly, this method provides rigorous estimates of the uncertainty of the projections made and therefore also provides measures of their goodness of fit.

In general, extrapolation of an empirical model cannot extend very far beyond the limits of the original data (say 10 percent) before the confidence limits diverge widely. Therefore, empirical models cannot usefully predict sea level very far into the future. Nonetheless, a good-quality 100-year-long tide gauge record should provide about a 20-year forward prediction within reasonable confidence limits. This should be sufficient to manage coastal development with a short design life and also to provide a good basis on which to develop adaptive and mitigation strategies.

6.2.1.9.2 Deterministic models

At the other extreme from empirical modeling in terms of computational complexity are deterministic computer programs. Based on the fundamental laws of physics, deterministic models can be used to make calculations of the likely position of future sea level based on theoretical grounds. The procedure involves initially developing scenarios of future economic activity and hence potential emissions of greenhouse gases. These scenarios are used to estimate the changes in radiative forcing and hence changes in global temperature. These data are then used in turn to estimate the response of the oceans and cryosphere in terms of ice melt, thermosteric expansion, and sea-level change.

Such modeling is based on the assumptions that all relevant factors are known and taken into account, that adequate theoretical understanding exists and can be expressed mathematically, and that the scenarios considered capture the actual trajectory of future events. These assumptions are not necessarily true.

The general circulation model (GCM) calculations of IPCC research groups are of the deterministic type (see Figure 6.2.1.9.1), and their outcomes are referred to as *projections* because, unlike empirical predictions, they do not have statistically meaningful confidence limits.

The projected changing global sea level generated by ocean warming and ice melting comprises the kernel of the IPCC's computer models

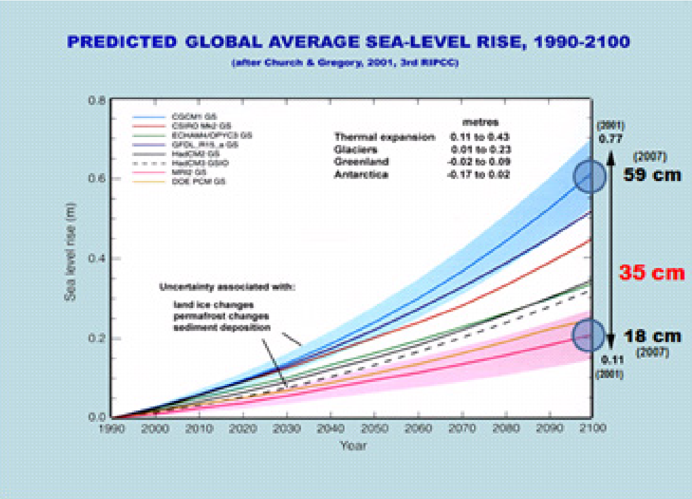

Figure 6.2.1.9.1. IPCC projections of sea-level rise between 1990 and 2100. Adapted from Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change.*

of the climate system. Ocean expansion can be directly related to warming of the surface mixed layer, but the melting of land ice is a more complex calculation that requires precise specification of surface temperatures. Ice does not necessarily melt if the surface temperature rises above 0° C; a small error can therefore make the difference between no melting and no sea-level change or actual melting and sea-level rise.

One difficulty with the deterministic approach is that it has proved difficult to identify the relative contributions to historical sea-level rise associated with the parameters modeled, so sea-level models have not predicted past sea levels well. It therefore remains unclear precisely how glacier and ice sheet behavior contribute to sea-level changes, although progress has been made since the first formal working group started their investigations in 1983 (Pfeffer, 2011). Thermosteric and halosteric sea-level changes also are not well constrained (Johnson and Wijffels, 2011). Since the Argo ocean-temperature profiling float array became fully operational in November 2007, some progress has been made on balancing the sea-level budget for the past decade (Leuliette and Willis, 2011), but it is not yet possible to extend the relationships back into the past with any degree of confidence (Wunsch *et al.,*2007).

The range of possible future sea-level changes projected by the IPCC and its predecessors has decreased progressively since the earliest reports produced for the UNEP (Hoffman *et al.,*1983). Due to the wide range of early projections and uncertainty about their validity, a future sea-level rise of 1 meter was commonly assumed for coastal impact assessments (SCOR Working Group 89, 1991), and that projection was included in the IPCC's *Second Assessment Report* in 1995. Considering the projections then currently used for coastal management, in its 2001 *Third Assessment Report* the IPCC provided a range of computer-generated projections for sea-level rise by 2100 of between 11 cm and 77 cm (Figure 6.2.1.9.1). They also estimated the current rate of sea-level rise of +1.8 mm/y was made up of contributions of 0.4 mm/y from thermal ocean expansion, 0.7 mm/y from ice melt, and 0.7 from dynamic oceanographic causes.

In the 2007 *Fourth Assessment Report* and using similar modeling, the IPCC adjusted the projected rise of sea level in 2100 to a range of 18–59 cm. The bottom end of this range corresponds with the 18 cm rise in sea level that results from extrapolating out to 2100 the long-term tide gauge rate of rise of 1.8 mm/y.

Church *et al.* (2011) compared the projections tuned by tide gauge data against the satellite altimetry trends, and Church and White (2011) reconstructed tide gauge data, concluding sea level is rising at the upper end of the IPCC projections. In contrast, the long-term tide-gauge- based sea-level rise reported by Church and White (1.7±0.2 mm/y), which they note is consistent with many other studies, falls right at the bottom of the IPCC projections (1.8 mm/y).

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6.2.1.9.3 Semi-empirical models

Between empirical and deterministic models lie other modeling techniques of moderate complexity that are collectively termed semi-empirical models. These models derive a relationship between sea level and temperature and then combine that relationship with a projected temperature scenario to estimate future sea-level rise. To their proponents, semi-empirical models are attractive because they are claimed to be superior to empirical models in making projections far into the future. Some of the most frequently cited are those by Rahmstorf (2007a), Vermeer and Rahmstorf (2009), Grinstead *et al.* (2010), and Rahmstorf *et al.* (2012).

The published results from semi-empirical models produce the highest and most alarming estimates of rates of future sea-level change so far published (between 0.8 and 1.8 m by 2100), and they conflict with projections based upon empirical or deterministic modeling. Accordingly, they are controversial and have attracted substantial criticism in the peer-reviewed scientific literature (Holgate *et al.*; Schmith *et al.*, 2007; Rahmstorf, 2007b).

The first of the semi-empirical studies (Rahmstorf, 2007a) proposed sea-level rise is a lagged response to temperature rise due to the greenhouse effect heating the ocean; the contribution from melting ice is also said to be a delayed response. These assumptions are directly contradicted by our knowledge of the last post-glacial sea-level rise (PALSEA, 2010; Section 6.2.1.1). In addition, the iterative smoothing process used by Rahmstorf during analysis has the effect of truncating the declining rate of sea-level rise observed in recent decades and inflating the correlation between sea level and temperature. The modeling also depends on the accuracy of IPCC emission scenarios known to be inaccurate (Castles and Henderson, 2003).

Some of these criticisms were taken into account in a modified version of the model, which includes an additional term and uses less smoothing, published by Vermeer and Rahmstorf (2009) (see Figure 6.2.1.9.2). However, the new term in the model reduces the effect of the slower rate of sea-level rise observed this century and maximizes the faster rate of the 1990s. These observed changes correspond to well-recognized decadal variability that is neither taken into account nor replicated in the 2009 Vermeer and Rahmstorf study.

The most recent iteration of Rahmstorf's semi-empirical model was published by Rahmstorf *et al.* (2012). This version of the model utilized several sea-level reconstructions, although only three are reported in the paper: the initial Church and White (2006) reconstruction; the revised global sea-level reconstruction of Church and White (2011); and the Jevrejeva *et al.* (2009) reconstruction. The 2011 reconstruction led to lower future sea-level rise than the older datasets, leading Rahmstorf *et al.* (2012) to argue the 2009 projection (based on outdated data) is the most accurate.

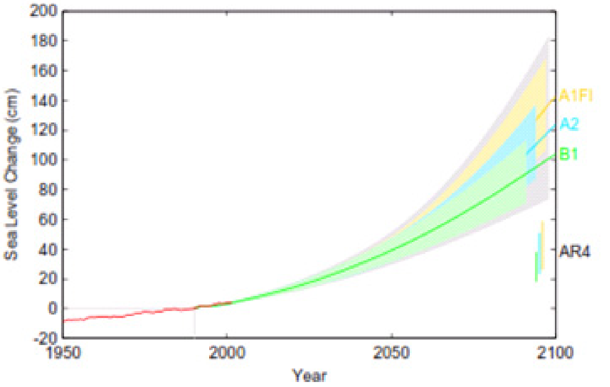

Figure 6.2.1.9.2. Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three emission scenarios (labeled on right). Adapted from Vermeer, M. and Rahmstorf, S. 2009. Global sea-level linked to global temperature, *Proceedings of the National Academy of Sciences* **106**: 21527–21532, Figure 6.

The semi-empirical models suffer from a fatal flaw: They include no probability analysis. Yes, these studies project the possible magnitude of a future rise. But because hazard is defined in terms of both magnitude and frequency, by not expressing the probability they give only one half of the story. The important other half is that although a higher rate of rise than that observed historically is possible, it is also extremely unlikely.

Conclusions

The controversy surrounding the accuracy and policy usefulness of published semi-empirical models of sea-level change remains unresolved. Semi-empirical models have several known flaws, and given that both empirical and GCM modeling yield more modest projections of future sea level, semi-empirical model projections should be viewed with caution until their flaws are addressed (e.g., Church *et al.*, 2011).

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6.2.1.10. Mechanisms of sea-level change

Key issues in understanding eustatic (global) sea-level change include the degree to which glacial meltwater is causing an increase in ocean mass, the degree to which global warming may be causing thermosteric ocean expansion and hence sea-level rise, and the relative magnitude of direct human interferences with the fresh water budget such as dam building and ground water mining.

Research on most of these topics has been touched upon in many of the preceding sections of this chapter. We add below summaries of a small number of other papers conveniently handled under the three subheadings of 6.2.1.10.

6.2.1.10.1. Ice melt

Earlier Research

Papers addressing the issue of land-based ice melt as a cause of global sea-level rise include the following:

- Bindschadler (1998) analyzed the historical retreat of the West Antarctic Ice Sheet in terms of its grounding line (the boundary between the floating ice shelf and the "grounded" ice resting on bedrock) and ice front. He found the retreat of the ice sheet's grounding line has been faster than that of its ice front since the time of the last glacial maximum, which resulted in an expanding Ross Ice Shelf. Although the ice front now appears to be nearly stable, there are "indications that its grounding line was retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years." Such a retreat would result in a sustained sea-level rise of 8–13 cm per century. Bindschadler acknowledges even the smallest of these rates of rise would require a large negative mass balance for all of West Antarctica, a finding not supported by the data.
- Reeh (1999) summarized earlier work on the mass balance of the Greenland and Antarctic ice sheets. He concluded their future contribution to global sea level depends as much upon their past climatic and dynamic history as it does upon future climate. With respect to potential climate change, Reeh estimated a 1°C warming would create little net change in mean global sea level; Greenland's contribution would be a sea-level rise of only 0.30 to 0.77 mm/yr, while Antarctica's contribution, given that it is accreting mass, would be a sea-level fall of about 0.20 to 0.70 millimeters per year.
- Vaughn *et al.* (1999) used more than 1,800 measurements of the surface mass balance of Antarctica to produce an assessment of yearly ice accumulation over the continent. They found the "total net surface mass balance for the conterminous grounded ice sheet is 1,811 Gt yr-1 (149 kg m-2 yr-1) and for the entire ice sheet including ice shelves and embedded ice rises, 2,288 Gt yr-1 (166 kg m-2 yr-1)." These values are about 18 percent and 7 percent higher than current estimates derived about 15 years earlier. Some of the discrepancy may be explained by changes in net icefall over more recent years. The uncertainty leads Vaughn *et al.* to note, "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea-level change."
- Cuffey and Marshall (2000) reevaluated previous model estimates of the Greenland ice sheet's contribution to sea-level rise during the last interglacial using a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. Their results suggest the Greenland ice sheet was much smaller during the last interglacial than previously thought, with melting of the ice sheet then contributing between 4 and 5.5 meters to sea-level rise. Hvidberg (2000) noted this finding suggests "high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change."
- Wild and Ohmura (2000) studied the mass balance of Antarctica using two general circulation

models developed at the Max Planck Institute for Meteorology in Hamburg, Germany: the older ECHAM3 and a new and improved ECHAM4. Under a doubled atmospheric CO_2 scenario, the two models were in close agreement in their mass balance projections, with both predicting increases in ice sheet growth and therefore decreases in sea level.

- Van der Veen (2002) stressed the need to use probability density functions rather than single model outputs for policy-related sea-level research. He comments, "the validity of the parameterizations used by [various] glaciological modeling studies to estimate changes in surface accumulation and ablation under changing climate conditions has not been convincingly demonstrated." Uncertainties in model parameters are so great they yield a 95% confidence range of projected meltwater contributions from Greenland and Antarctica that encompass global sea-level lowering as well as rise by 2100 A.D., for all of IPCC's low, middle, and high warming scenarios. Van der Veen concluded confidence in current ice sheet mass balance models "is quite low," today's best models "currently reside on the lower rungs of the ladder of excellence," and "considerable improvements are needed before accurate assessments of future sea-level change can be made."
- Wadhams and Munk (2004) attempted "an independent estimate of eustatic sea-level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level)." Their analysis produced "a eustatic rise of only 0.6 mm/year," and when a steric contribution of 0.5 mm/year is added to the eustatic component, "a total of 1.1 mm/year, somewhat less than IPCC estimates," was the final result. Interestingly, the continental runoff "allowed" after subtracting the effect of sea-ice melt "is considerably lower than current estimates of sub-polar glacial retreat"; consonant with the mass balance models discussed above, this suggests a negative contribution to sea-level from polar ice sheets (Antarctica plus Greenland) or other non-glacial processes. Wadhams and Munk note, "we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive or negative contribution."
- Oppenheimer and Alley (2005) discuss the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other, for both the West Antarctic and Greenland Ice Sheets. They conclude our knowledge is simply too incomplete to know whether these ice sheets have made a significant contribution to sea-level rise over the past few decades.
- Velicogna and Wahr (2006) used early measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the period 2002–2005. The two researchers conclude "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/yr of ice, equivalent to 0.4 ± 0.2 mm/yr of global sea-level rise." All of this mass loss came from the West Antarctic Ice Sheet; the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year.

The Velicogna and Wahr conclusion should be viewed as provisional because of the many estimates and adjustments necessary during data reduction (see Section 6.2.1.8 for additional comments on the difficulty of using GRACE data). The adjustment for post-glacial rebound alone exceeded the signal being sought by nearly a factor of five. Moreover, the study covers less than a three-year period, and the result compares poorly with the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent nine-year period was only 0.08 mm/yr.

- Ramillien *et al.* (2006) also used GRACE data to derive mass balance estimates for the East and West Antarctic ice sheets for the years 2002–2005. They calculated a loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East Antarctica, totaling a net ice loss for the entire continent of 40 km^3/year, a mean sea-level rise of 0.11 mm/year. This result is almost four times less than that calculated by Velicogna and Wahr. Ramillien *et al.* caution in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."
- Wingham *et al.* (2006) analyzed European remote sensing satellite altimeter data to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. They found "72% of the Antarctic ice sheet is gaining 27 ± 29 Gt per year, a sink of ocean mass sufficient to lower global sea levels by 0.08 mm per year." Wingham *et al.* contend this net extraction of water from the global ocean was driven by mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica.

- Remy and Frezzotti (2006) reviewed the results produced by estimating mass balance in three ways: measuring the difference between mass input and output; monitoring the changing geometry of Antarctica; and modeling both the dynamic and climatic evolution of the continent. They report “the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale [centuries].” They also note, “later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level.”
- Shepherd and Wingham (2007) reviewed 14 satellite-based estimates of sea-level contributions arising from wastage of the Antarctic and Greenland Ice Sheets since 1998. The earlier studies included standard mass budget analyses, altimetry measurements of ice-sheet volume changes, and measurements of the ice sheets’ changing gravitational attraction. The results ranged from a sea-level-rise-equivalent of 1.0 mm/year to a sea-level-fall-equivalent of 0.15 mm/year. Shepard and Wingham concluded the current best estimate of the contribution of polar ice wastage from Greenland and Antarctica to global sea-level change was a rise of 0.35 mm/yr, i.e., a rate of 35 mm/century.

An important factor in many of these ice budget papers is the degree to which glacial wastage rates vary from year to year. For example, two of Greenland’s largest outlet glaciers doubled their rates of mass loss in less than a year in 2004—causing the IPCC to claim the Greenland Ice Sheet was responding much more rapidly to global warming than expected—but by 2006 the mass loss had decreased to near the previous rates. Thus Shepherd and Wingham warn “special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends.”

- Krinner *et al.* (2007) applied the LMDZ4 atmospheric general circulation model of Hourdin *et al.* (2006) to simulate Antarctic climate for the periods 1981–2000 (to test the model’s ability to adequately simulate recent conditions) and 2081–2100 (to assess the future mass balance of the Antarctic Ice Sheet and its impact on global sea level). They conclude the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year, which corresponds to a sea-level decrease of 1.2 mm per year by the end of the twenty-first century. This would lead to a cumulated sea-level decrease of about 6 cm. They note the simulated temperature increase “leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air,” where the extra moisture falls as precipitation and causes the continent’s ice sheet to grow.
- In a study of Alaskan and nearby Canadian glaciers, Berthier *et al.* (2010) pointed out earlier estimates of mass loss from Alaskan and nearby glaciers (Arendt *et al.*, 2002; Meier and Dyurgerov, 2002; Dyurgerov and Meier, 2005) relied on extrapolating site-specific measurements to the entire region. For example, Arendt *et al.* (2002) used laser altimetry to measure elevation changes on 67 glaciers, but those glaciers represented only 20 percent of the area of the ice field.

To overcome this and other deficiencies, Berthier *et al.* attempted to calculate ice elevation changes for nearly three-quarters of the ice-covered areas in Alaska by measuring elevation changes derived from sequential digital elevation models for the period 1962–2006. They found, “between 1962 and 2006, Alaskan glaciers lost 41.9 ± 8.6 km^3 of their volume over the measured period, thereby contributing 0.12 ± 0.02 mm/yr to sea-level rise.” This estimate is 34 percent less than those of Arendt *et al.* (2002) and Meier and Dyurgerov (2002), an indication of the inherent errors in this type of research. Berthier *et al.* comment, “estimates of mass loss from glaciers and ice caps in other mountain regions could be subject to similar revisions.”

- Nick *et al.* (2013) developed a glacier flow model incorporating the dynamic behavior of marine glacial termini affected by ocean conditions. This model was applied to four marine-terminating glaciers that account for 22 percent of the flow from the Greenland Icecap. Assuming 2.8° C of warming by 2100, they simulated the atmospheric and oceanic effects on ice discharge and projected a sea-level contribution of 19–30 mm by AD 2200 (0.01–0.06 mm/y per glacier after an initial rapid loss associated with over-deepenings in the glacier troughs). These estimates are considerably lower than those derived by Pfeffer *et al.* (2008) of 36–118 mm for the 22 percent of glacier flow (or 165–538 mm for all of Greenland) by AD 2100.

Conclusions

Considerable uncertainty attends our knowledge of the water balance of the world’s oceans and the melting of on-land ice. These uncertainties must be resolved before we can confidently project effects such as sea-level change.

It appears there has been little recent change in global sea level due to wastage of the West Antarctic Ice Sheet, and such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall. In such circumstances the sum of the response of the whole Antarctic Ice Sheet might well compensate for any long-term wastage of the Greenland Ice Sheet, should that happen.

Regarding the Northern Hemisphere, the Arctic regions have been cooling for the past half-century, and at a very significant rate, making it unlikely Greenland's frozen water will be released to the world's oceans anytime soon. This temperature trend is just the opposite—and strikingly so—of that claimed for the Northern Hemisphere and the world by the IPCC. Accompanying the cooling, the annual number of snowfall days over parts of Greenland has also increased strongly, so an enhanced accumulation of snow there may be compensating for the extra runoff coming from mountain glaciers that have been receding.

The balance of the evidence from both hemispheres indicates little net sea-level change is currently occurring as a result of accentuated ice melt. It remains entirely possible the global cryosphere is actually growing in mass.

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6.2.1.10.2. Thermosteric

Lombard *et al.* (2005) used the global ocean temperature data of Levitus *et al.* (2000) and Ishii *et al.* (2003) to investigate the thermosteric, or temperature-induced, sea-level change of the past 50 years. A net rise in sea level occurred over the full half-century period, but superimposed on that are marked decadal oscillations that represent ocean-atmosphere climatic perturbations such as the El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation. Lombard *et al.* recognized these as thermosteric trends over 10-year windows that showed large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (-1 to -1.5 mm/year for the decade centered on 1980).

The record shows only an overall trend because it began at the bottom of a trough and ended at the top of a peak. In between these two points, there were both higher and lower values, so one cannot be sure what would be implied if earlier data were available or what will be implied as more data are acquired. Lombard *et al.* noted similar sea-level trends that occur in TOPEX/Poseidon altimetry over 1993–2003 are “mainly caused by thermal expansion” and thus probably not a permanent feature. They conclude, “we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone.”

If even the 50 years of global ocean temperature data we possess are insufficient to identify accurately the degree of global warming and related sea-level rise that has occurred over the past half-century, it will be many decades before satellite altimetry can identify a real climatic trend.

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6.2.1.10.3. Dam storage and groundwater depletion

Two human on-land development practices can have a material effect on sea level: the building of dams and reservoirs, which withhold water that would otherwise have flowed to the ocean; and the extraction of groundwater, which, after use, contributes water to the ocean that otherwise would have remained stored on the continent. The net freshwater run-off is thereby altered, with the first practice acting to lower sea level and the second practice helping to raise it.

Though they act in opposite directions and are small in the natural scheme of things, these effects are not entirely negligible (e.g., Sahagian *et al.*, 1994; Gornitz *et al.*, 1997; Konikow and Kendy, 2005, Huntington, 2008; Lettenmaier and Milly, 2009; Milly *et al.*, 2010). Konikow (2011) recently summarized the situation with respect to groundwater removal by compiling the first comprehensive aquifer-based estimate of changes in groundwater storage using direct volumetric accounting. Konikow then compared the groundwater depletion results he obtained with sea-level rise observations.

Konikow established groundwater depletion over the period 1900–2008 was about 4,500 km^3, equivalent to a global sea-level rise of 12.6 mm, or just over 6 percent of the total observed rise. Perhaps not surprisingly, the rate of groundwater depletion has increased markedly since about 1950, with maximum rates occurring during the most recent period (2000–2008), when extraction averaged ~145 km^3/year. The average rate of sea-level rise over the twentieth century was 1.8 ± 0.5 mm/year (Church *et al.*, 2011); Konikow’s work suggests on average 0.12 mm/yr of this rise may have resulted from additional groundwater runoff.

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6.2.1.11. Policy: What is the problem?

The fear that human carbon dioxide emissions may cause dangerous sea-level rise beyond natural rates and levels has focused policy attention on cutting emissions. The preceding parts of Section 6.2 have demonstrated there is very little evidence to support the CO_2-sea level rise hypothesis. No evidence (as opposed to computer model speculation) shows the human component of atmospheric carbon dioxide levels is materially influencing sea level to behave outside its usual natural envelope of change.

Based on geological studies, it appears global sea-level rise has been taking place at a slowing rate over the past 10,000 years (cf., Figure 6.2.1.1.2). At specific locations, this rising trend interacts with tectonic factors, isostatic effects, and multidecadal rhythmicity to produce different patterns of local relative sea-level change that vary from place to place and region to region (Figure 6.2.1.8.1.1). It is also established by many studies that over the past 150 years eustatic sea level has been rising at an average rate of about 1.8 mm/y, which represents the slow continuation of a melting of the ice sheets that began about 17 ka. The IPCC estimates 1.1 mm of this rise can be accounted for by the combined effects of continuing ice melt (~0.4 mm/y) and steric ocean expansion (~0.7 mm/y), and that the residuum, if correctly estimated, probably relates to dynamic oceanographic and meteorological factors.

There is, therefore, no scientific basis for the oft-repeated suggestion that "global warming" will melt so much ice that sea levels will imminently rise by Al Gore's imagined 20 feet. In four successive *Assessment Reports* between 1990 and 2007, the IPCC has reduced its estimate of the maximum sea-level rise by the year 2100 from 367 to 124 to 77 to 59 cm, a reduction of the speculated rise of more than 80 percent. Moreover, IPCC 2007 assumed most of the projected increase arises from a slow (centuries) thermosteric expansion of the oceans, which produces a sea-level rise of only 20–60 cm per 1°C increase in globally averaged warming (Church *et al.,*2011). Furthermore, warming is currently not occurring at the projected rate. Should they continue to melt, glaciers and ice caps are expected to contribute another 12±4 cm by 2100 (Church *et al.,*2011). Ice sheet contributions are less certain because of large variations in estimates of ice volume losses. However, an upper estimate based on extrapolating a short record is 56 cm by 2100 (Pfeffer, 2011).

Conclusions

The problem is not global sea-level change, which, using a naïve forecasting approach, is projected to rise by only about 18 cm by 2100. Instead the problem is uncertainty. That uncertainty applies to future global temperature change, future ice accretion or melting, and future global sea-level change—and it is profound.

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Management and planning for the real hazard

Sea levels change naturally, constantly, and all over the world at different rates and in opposing directions. In addition, the effect of sea-level change is almost exclusively a matter of coastal management, a fact that has not been widely recognized. Outside of very shallow coastal waters, whether the sea level is higher or lower is of no practical concern for shipping activities or other human ocean uses such as erecting offshore petroleum production platforms or laying deep-sea communications cables. Thus at the heart of the issue of sea-level policy lies the need for an understanding of coastal processes.

The position and stability of a shoreline depends upon a number of factors. One of these is local mean sea level. But several other important natural processes also operate within and upon the coastal environment, including geomorphology, sediment supply, and mean and extreme conditions of wind, weather, and near-shore oceanography. The shoreline also is affected by human development.

In most countries, coastal management is traditionally undertaken by a local or regional council of some type, operating within a legal framework provided by either a state or national government (French, 1997). The local agencies deal with such matters as beach erosion and harbor dredging, and they establish and enforce land-use and building regulations addressing what types of structures may be built where. In implementing coastal policy, lawmakers and their staff traditionally have been guided by experienced, legally accountable, professional coastal engineers and scientists. Until recently, therefore, cost-benefit analysis of coastal policy was generally alive and well at the local and regional level of governance and administration.

Which is, of course, not to say historic coastal management has been perfect. One particular defect has been inadequate control over dense coastal development that later proves to be inadequately sited to withstand the effects of rare and episodic super storms. The "hurricane" Sandy storm in northeastern USA provides a case in point. The strong wave surges and winds that imposed such destruction on the northeast's poorly located coastal communities were caused by the merging of two separate storm systems. Though this was a rare event, in a general sense it was entirely predictable, and the occurrence of Sandy should act as a wake-up call for the need for more cautious attitudes to coastal development.

Since 1988, traditional, locally oriented coastal management has increasingly come to be replaced by planning based on global environmental principles, as the IPCC commenced advising governments about global sea-level change. The advent of IPCC's global warming advice usurped the traditional policy process through which governments drew their advice about sea-level change from statutory authorities concerned with harbor and tidal management and from formal governmental scientific agencies. Because the IPCC is tasked to ponder global warming, after its formation the focus of governments shifted from seeing sea-level change as a beaches, ports, harbors, and navigational issue to seeing it as an environmental issue related to hypothetical global warming caused by human carbon dioxide emissions.

As part of this change, attention shifted away from basing public policy on the use of measured tide gauge records of sea level (see Figure 6.2.1.2.1) to basing it on the theoretical projections of computer models (such as Figures 6.2.1.9.1 and 6.2.1.9.2). By the turn of the twentieth century, governments around the world, and their advisory scientists, were basing their sea-level planning almost exclusively on the advice of the IPCC; i.e., on unvalidated computer model predictions tied not to accurate local sea-level measurements but to a theoretical geoid that floats in mathematical space.

Because IPCC sea-level predictions were and are for a global average sea level, we thus arrived at our present unsustainable position, which is one of governments fashioning policy and new laws predicated upon a notional statistic and in almost complete disregard of the local real measurements available from tide gauge networks. Many countries or states have passed measures that require their coastal authorities to base planning on IPCC's assumed 59 cm rise by 2100, or higher. For example, the Australian states of Victoria and New South Wales have set planning benchmark levels of 80 cm and 90 cm, respectively.

Abandoning traditional, empirical methods of dealing with coastal management issues and adopting (sometimes exaggerating) the IPCC's uncertain, model-based sea-level projections has introduced much additional and unrecognized uncertainty into policy planning. Uncertainty surrounds the global temperature projections that feed into sea-level modeling and affects the relationship between global temperature change and polar land ice melting rates. Moreover, we lack accurate knowledge of the glacial isostatic anomaly.

Conclusions

Based on this discussion and the other material presented in this chapter, three obvious policy guidelines present themselves for implementation.

Abandon "let's stop global sea-level rise" policies
No justification exists for continuing to base sea-level policy and coastal management regulation on the outcomes of deterministic or semi-empirical sea-level modeling. Such modeling remains highly speculative. Even if the rate of eustatic sea-level change was known accurately, the practice of using a notional global rate of sea-level change to manage specific coastal locations worldwide is irrational, and it should be abandoned.

Recognize the local or regional nature of coastal hazard
Most coastal hazard is intrinsically local in nature. Other than periodic tsunamis and exceptional storms, it is the regular and repetitive local processes of wind, waves, tides, and sediment supply that fashion the location and shape of the shorelines of the world.

Yes, local relative sea level is an important determinant, but in some localities it is rising and in others falling. Accordingly, there is no "one size fits all" sea-level curve or policy that can be applied. Coastal hazard can be managed effectively only in the context of regional and local knowledge and using data gathered by site-specific tide gauges and other relevant instrumentation.

Use planning controls that are flexible and adaptive
The shoreline is a dynamic geomorphic feature that quite naturally moves with time in response to changing environmental conditions. Many planning regulations already recognize this; for example, by applying minimum building setback distances or heights from the tide mark. In addition, engineering solutions (groynes, breakwaters, sea-defense walls) often are used to stabilize a shoreline. If they are effective and environmentally acceptable, such solutions should be encouraged.

Nevertheless, occasional damage will continue to be imposed from time to time by large storms or other unusual natural events, no matter how excellent the preexisting coastal engineering and planning controls may be. In these circumstances, the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur. It is the height of futility and a waste of scarce financial resources to attempt to "control" the size or frequency of large natural events by expecting that reductions in human carbon dioxide emissions will moderate climate "favorably," including expectations of a reduced rate of global sea-level rise.

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6.2.2. Ocean Heat

Earth's climate is not controlled solely by the atmosphere but also to a large degree by the heat stored in the ocean, which has a 3,300 times greater heat capacity than the atmosphere. With an average global circulation time of roughly 1,000 years, compared with one year for the atmosphere, changes in the release or uptake of ocean heat operate over the longer multidecadal, centennial, and millennial time scales associated with climate change, as opposed to weather variability.

The exchange of ocean heat via currents and wind-enhanced ocean-atmosphere interactions drives weather at all scales of both space and time. Particular, repetitive weather patterns occur over the ocean itself and exercise far-reaching influence on adjacent landmasses. For example, the wet, warm winds that blow from the ocean to the continental interior in the Pacific Northwest of USA (Chinook wind, in original usage) can raise winter temperature from -20°C to more than +10°C and melt 30 cm or more of snow in a single day. Monsoon systems are another case in point, where seasonal differential heating of a landmass and its nearby ocean cause a reversal of winds from offshore to onshore at the start of the monsoon, often causing torrential rainfall deep into the continental interior.

Despite its critical importance for climatic studies, we have a poor record of ocean heat observations, and it is only since the inception in 2004 of the Argo global network of more than 3,000 ocean profiling probes that we have an adequate estimate of ocean temperatures and heat budget. Though Argo data are in their infancy and subject to adjustment for errors, early indications are that the oceans are currently cooling (Loehle, 2009).

Shaviv (2008) explored some of the key issues relating to change in ocean heat as a driver of climate change, particularly in response to solar variations. He writes, “climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales,” citing numerous references. Nonetheless, many scientists decline to accept the logical derivative of this fact: Solar variations are driving climate changes. They say measured or reconstructed variations in total solar irradiance (TSI) seem too small to be capable of producing observed climate change.

That concern can be addressed in two ways. The first is to observe that aspects of Earth-sun energy interrelations other than TSI are known to play a role, and perhaps a significant role, in climate change. These mechanisms, addressed in Chapter 3, include:

- Variations in the intensity of the Sun’s magnetic fields on cycles that include the Schwabe (11 year), Hale (22 year), and Gleissberg (70–90-year) periodicities;

- The effect of the sun’s plasma and electromagnetic fields on rates of Earth rotation, and therefore the length of day (LOD);

- The effect of the sun’s gravitational field through the 18.6-year-long Lunar Nodal Cycle, which causes variations in atmospheric pressure, temperature, rainfall, sea level, and ocean temperature, especially at high latitudes;

- The known links between solar activity and monsoonal activity, or the phases of climate oscillations such as the Atlantic Multidecadal Oscillation, a 60-year-long cycle during which sea surface temperature varies ~0.2° C above and below the long-term average, with concomitant effects on Northern Hemisphere air temperature, rainfall and drought; and

- Magnetic fields associated with solar flares, which modulate galactic cosmic ray input into Earth’s atmosphere and in turn may cause variations in the nucleation of low-level clouds at up to a few km high (Ney, 1959; Dickinson, 1975; Svensmark, 1998). This causes cooling, a 1 percent variation in low cloud cover producing a similar change in forcing (~4 W/m^2) as the estimated increase caused by human greenhouse gases. This possible mechanism is controversial and is being tested in current experiments devised at the European Organization for Nuclear Research (CERN). But irrespective of the results of these experimental tests and of the precise causal mechanism, Neff *et al.* (2001) have provided evidence from palaeoclimate records for a link between varying cosmic radiation and climate (see Figure 6.2.2.1). Using samples from a speleothem from a cave in Oman, Middle East, they found a close correlation between radio-carbon production rates (driven by incoming cosmic radiation, which is solar-modulated) and rainfall (as reflected in the geochemical signature of oxygen isotopes).

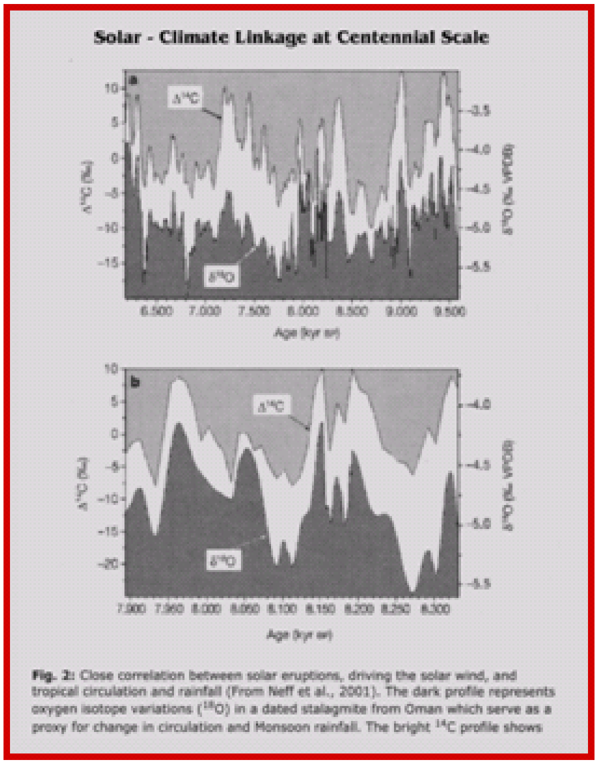
Solar - Climate Linkage at Centennial Scale

Fig. 2: Close correlation between solar eruptions, driving the solar wind, and tropical circulation and rainfall (From Neff et al., 2001). The dark profile represents oxygen isotope variations (^{18}O) in a dated stalagmite from Oman which serve as a proxy for change in circulation and Monsoon rainfall. The bright ^{14}C profile shows

Figure 6.2.2.1. Correlation between proxies for incoming cosmic radiation (radiocarbon production) and rainfall (oxygen isotope signature) from an Oman spleothem. Adapted from Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A. 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411**: 290–293.

- The 1,500-year-long Bond Cycle is probably also of solar origin, and another climate rhythm of similar length, the Dansgaard-Oeschger (D-O) cycle, occurs especially in North Atlantic glacial sediments deposited about 90,000–15,000 years ago.

A second way of resolving the too-weak-TSI dilemma would be the discovery of an amplification mechanism of the weak solar radiation signal. Shaviv (2008) makes a good case for the existence of such an amplifier. Shaviv used the oceans as a calorimeter with which to measure the radiative forcing variations associated with the solar cycle. He studied “three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations, each of which can be used independently to derive the oceanic heat flux.”

Shaviv discovered large variations in oceanic heat content associated with the 11-year solar cycle. In addition, the datasets “consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance.” This clearly implies the existence of an amplification mechanism, although without pointing precisely to what that might be.

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6.2.2.1. Ocean Heat Measurement

Ocean heat content is determined by extrapolating vertical temperature and salinity profile data collected by a range of techniques at different sampling densities (Emery and Thomson, 2001). The specific heat of seawater is a complex function of temperature, salinity, and pressure (Fofonoff and Millard Jr., 1983), so all three parameters are required to estimate the heat content within a profile. Due to the high heat capacity of water (~4 kJ.kg^{-1}.°C^{-1}), small changes in temperature result in significant changes in specific heat depending on salinity and pressure (see Figure 6.2.2.1.1). Small errors in temperature measurement thus result in large errors in estimated heat content. This leads to special difficulties in the modern use of older data. Early data obtained by hydrocasts were manually error-checked by comparing the measured profiles with the “expected” or “known” trends, leading Emery and Thomson to comment, “As a matter of curiosity, it would be interesting to determine the number of deep hydrocast data that were unknowingly collected at hydrothermal venting sites and discarded because they were ‘erroneous.’”

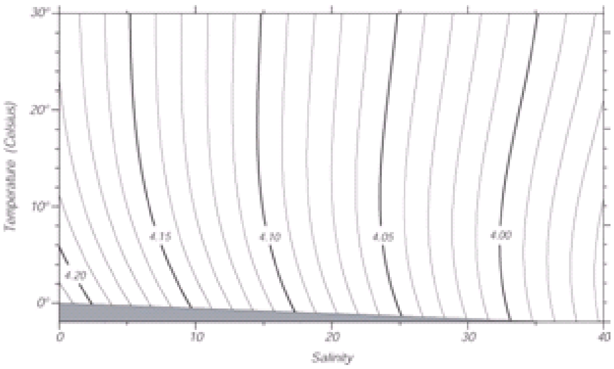

Figure 6.2.2.1.1. Specific heat of seawater in J.g^{-1},°C^{-1} at atmospheric pressure for a typical range of ocean temperatures and salinities. Stuart, Robert H. (2008) *Introduction to Physical Oceanography*. Chapter 5, The Oceanic Heat Budget, Figure 5.1. oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book.pdf.

Deep ocean conditions were measured by hydrocasts using different sensor types lowered and then raised to the surface. Typically the collected data displayed hysteresis[3] due to the relatively slow response times of the sensors. Subsequently, profiles were obtained by expendable bathythermographs (XBTs), which measure only a descent profile, or profiling floats that measured descent and ascent profiles in different locations to correct for variable periods of drifting between ascent/descent.

Surface layer temperatures have been measured by buckets, inlet temperatures for engine cooling

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[3] Data collected during the descent tended to be too warm, and during the ascent too cold. Averaging the two profiles was assumed to give a more reliable estimate of the true conditions.

systems, and thermistor strings suspended from surface buoys. Finally, the skin temperature of the ocean can be estimated from the infrared radiation emitted as observed by satellite or airborne sensors (Emery and Thomson, 2001). This wide range of measurement techniques makes direct comparisons of ocean heat between repeat surveys problematic.

In addition, the sample coverage of the oceans is relatively sparse, particularly before the Argo array of profiling floats achieved near global coverage in 2004. Hence, the measured heat contents are extrapolated over large volumes to estimate the global heat content. This has led some studies to conclude ocean heat can be determined only since 1993 (Lynman *et al.* 2010). Carson and Harrison (2008) demonstrated inferred warming of the ocean was largely a consequence of the data interpolation methodologies used, which tended to be biased toward the 30 percent of the ocean regions that warmed and ignored regions that had cooled.

Quite large variations among even recent studies are evident (Lynman *et al.*, 2010). Willis *et al.* (2009) compare results determined from different data sources over a three-year period (see Figure 6.2.2.1.2). All data taken together indicated cooling; XBT data and estimates from satellite altimetry indicated a slight cooling; and Argo data excluding known faulty floats indicated slight cooling. The faulty Argo floats strongly influenced the results. In addition, the Argo floats found lower ocean heat content than the other data sources. Since the proportion of data derived from Argo floats increased with time, Willis *et al.* suggest the combination of data sources also created a cooling bias.

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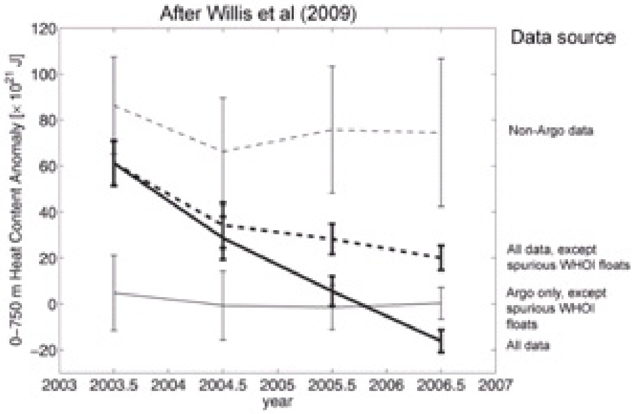

Figure 6.2.2.1.2. Comparison of global ocean heat content changes for the upper 750 m of using different combinations of data sources. Adapted from Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852, Figure 4.

6.2.2.2. Ocean Heat Trends

Willis *et al.* (2009) point out "as the Earth warms due to the buildup of greenhouse gases in the atmosphere, the majority of the excess heat is expected to go toward warming the oceans (Levitus *et al.*, 2005; Hansen *et al.*, 2005)." In contradiction of this expectation, a significant cooling in the ocean heat content anomaly (OHCA) was reported between 2003 and 2005 by Lyman *et al.* (2006).

As discussed in the previous section, Willis *et al.* (2009) concluded the cooling reported by Lyman *et al.* (2006) was an artifact caused by XBT warm bias and Argo cold bias because of the changing proportion of data sources over time. They concluded "OHCA does not appear to exhibit significant warming or cooling between 2003 and 2006." Willis *et al.* also note the absence of a significant cooling signal in the adjusted OHCA results "brings estimates of upper-ocean thermosteric sea level variability into closer agreement with altimeter-derived measurements of global mean sea level rise."

Domingues *et al.* (2008) adjusted their estimates of ocean heat content to match sea-level changes as determined by Church and White (2006). The period of analysis, from 1950 to 2003, excludes the Argo data. They found an increase in ocean heat content, mostly between 1970 and 2003, with significant multidecadal oscillations that do not fit volcanic eruptions or ENSO variations well.

Lynman *et al.* (2010) revised their earlier study and incorporated an analysis of uncertainties in other studies by examining the effect of different methodologies used to estimate ocean heat. Their analysis focused on the period 1993 to 2008; they found ocean heat increased over this period, mostly between 2000 and 2002, but there had been negligible changes in ocean heat since 2003.

Katsman and van Oldenburgh (2011a, b) considered the period 2003–2010 and note "the upper ocean has not gained any heat, despite the general expectation that the ocean will absorb most of the Earth's current radiative imbalance." Based on an ensemble of climate models, they attributed the lack of any gain in ocean heat to ENSO events resulting in an increased loss of heat to space and increased warming in the ocean depths due to reduced northwards transport of heat in the Atlantic Ocean. This interpretation is difficult to reconcile with the behavior of ocean circulation, and especially its climatic lag effects. For example, it can take almost a decade for the heat generated by an ENSO warm event in the Pacific to travel through the Indian Ocean, around the Cape of Good Hope, and up the Atlantic to feed into the Gulf Stream (see also Section 6.2.3 below).

Gouretski *et al.* (2012) consider ocean heating since 1900, but only for the upper 400 m. They found two distinct warming periods, between 1900 and 1940–1945 and between 1970–2003. They found patterns of heating in the upper 20 m mirrored global temperature patterns and appear to include an 11-year cycle and responses to ENSO events. They also noted a distinct flattening of the ocean heating trend for the twenty-first century.

Comparing the trends determined by Levitus *et al.* for 0–2,000 m and 700–2,000 m shown in Figure 6.2.2.2.1, it is clear the upper 700 m of the ocean is more variable than the lower layer. There is no evidence of an acceleration of warming in the lower layer in the twenty-first century.

Balmaseda *et al.* (2013) attempted to account for the lack of warming in the atmosphere and upper ocean by undertaking a reanalysis of the available data and estimating the total heat content of the ocean (upper 300 m, upper 700 m, and total water column). Their method involved adjusting numerical model simulations with observational data for the period 1958–2009, which is similar to the period considered by Levitus *et al.* (2012). Balmaseda *et al.* concluded over the final decade 30 percent of the ocean heat content increase occurred below 700 m, and this increase continued despite the hiatus of warming at the surface.

The authors suggest this represents an increase in the rate of warming of the deep ocean. However, as noted by Levitus *et al.* (2012), over the period 1955–2010 about 30 percent of the warming occurred between 700 and 2000 m, indicating the result reported by Balmaseda *et al.* (2013) is not unusual. The reanalysis data produced by Balmaseda *et al.* also show a greater response to volcanic forcing and ENSO events than is evident in observational datasets, suggesting the models may be exaggerating the effect of these processes. Finally, the decadal trends estimated from model results for depths below 700 m (Table 1 of Balmaseda *et al.*, 2013) indicate decadal changes not evident in Figure 6.2.2.2.1.

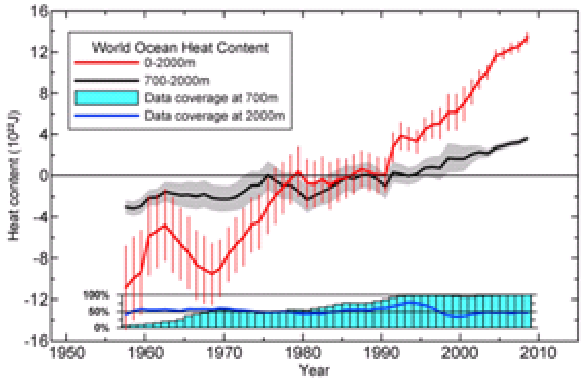

Figure 6.2.2.2.1. Smoothed (pentadal) ocean heat estimates for 0–2000 m and 700–2000 m determined by Levitus *et al.* (2012). The average temperature increases associated with the changed heat contents are 0.09°C and 0.18°C for the top 2000 m and 700 m respectively. Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., and Zweng, M.M. 2012. World ocean heat content and thermosteric sea level change (0-2000 m), 1955–2010: *Geophysical Research Letters* **39**: L10603–L10603.

Nuccitelli *et al.* (2012) presented a recalculated estimate of ocean heat content to 2,000 m between 1960 and 2008 (see Figure 6.2.2.2.2). Earlier estimates of OHC cover only the shallow ocean to 700 m and show little of the warming that is apparent in Figure 6.2.2.2.2. From their new compilation, Nuccitelli *et al.* conclude global warming is continuing. Their interpretation is at best partially valid, for several reasons.

First, Figure 6.2.2.2.2 shows warming between 2003 and 2008, when the record ends. This pattern is contradicted by the Argo profiling buoy database, which shows a flatlining or gentle cooling for 2003 to 2008. The Argo conclusion is supported by the available measurements of global sea-surface temperature, which also show cooling since 2000 (see Figure 6.2.2.2.3).

Second, no error bars are shown in Figure 6.2.2.2.2, yet they are likely to be greater than the range of change shown even for the post-2003 Argo time period; data before that date are unsystematic, with error bars so large the curve depicted is, at best, an educated guess. Third, the mechanisms that transmit incoming heat from the surface to intermediate and deep water masses have time constants of many years to centuries. Even if the depicted upper ocean warming were true, it would represent heat added to the ocean at least many decades if not centuries ago—which means it cannot have been caused by atmospheric CO_2.

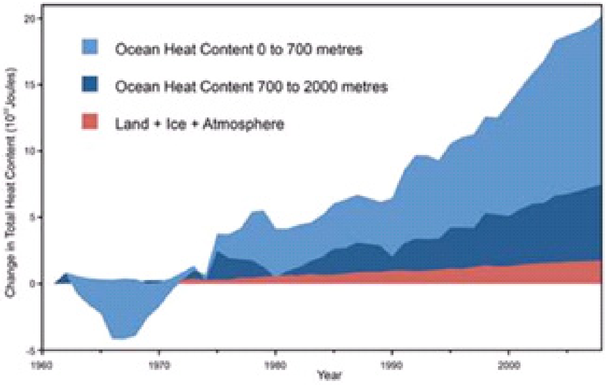

Figure 6.2.2.2.2. Ocean heat estimates. Nuccitelli, D., Way, R., Painting, R., Church, J., and Cook, J. 2012. Comment on "Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts." Physics *Letters A* **376**: 3466–3468.

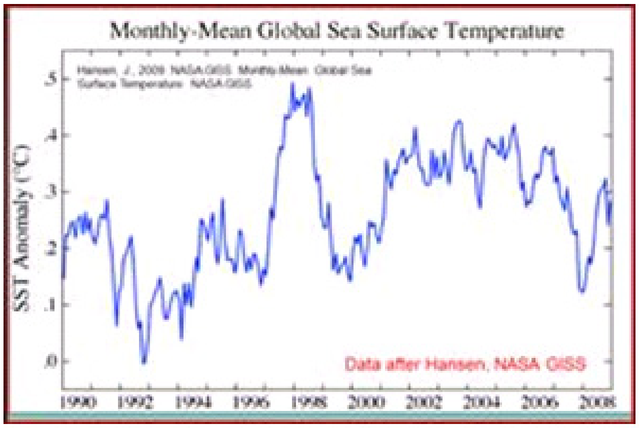

Figure 6.2.2.2.3. Mean global sea surface temperatures, 1990–2008. NASA 2008. http://data.giss.nasa.gov/gistemp/ 2008/.

Conclusions

At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 15 years or more of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming.

Increasingly, this problem has been finessed by the argument that the atmosphere holds only a small percentage of the world's heat, and what really counts is the 93 percent of global heat sequestered in the oceans. Yet no sign of significant or accelerated ocean warming exists.

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6.2.3. Ocean Circulation

6.2.3.1. The Cenozoic palaeo-ocean

The high specific heat of seawater makes ocean circulation the dominant mechanism for redistributing thermal energy within Earth’s climate system. Zachos *et al.* (2001) summarized the evolution of the global climate over the Cenozoic (last 65 million years) based on data obtained by the DSDP and ODP ocean drilling programmes (see Figure 6.2.3.1.1). It is evident that significant shifts in climate have been associated with major changes in ocean circulation. Major conclusions that can be drawn about ocean history from Figure 6.2.3.1.1, and the supporting references cited in Zachos *et al.* (2001), include the following:

- During the Eocene, the average temperature of the deep ocean declined by more than 7°C from ~12° C during the Eocene climatic optimum to ~4.5°C at the start of the Oligocene. This decline was associated with an increase in marine productivity, which had fallen after widespread benthic extinctions during the late Paleocene and early Eocene.
- The start of the Oligocene was associated with the opening of the Tasmania-Antarctica Passage between the Australia and Antarctic continents. This was associated with a reduction in the tropical linkages between the Pacific and Indian Oceans (strictly, their equivalents) north of Australia.
- During the Oligocene, the Drake Passage between the South America and Antarctic continents opened, allowing water to circulate around Antarctica and linking all the ocean basins. The change in ocean circulation due to the opening of the two passages was associated with the formation of an Antarctic ice cap and a further drop in deep ocean temperatures.
- The late Oligocene was marked by warming, before temperatures fell during the Miocene.
- At the start of the Pliocene the Panama Seaway between the North and South America continents closed, removing the tropical linkage between the Pacific and Atlantic Oceans. The tropical through-flow between the Pacific and Indian Oceans also was becoming more restricted. This resulted in the establishment of “modern” ocean circulation and is marked by the onset of Northern Hemisphere glaciation.
- The Pliocene and Pleistocene are characterized by glacial/interglacial climatic swings, suggesting the “modern” ocean circulation system makes Earth more sensitive to Milankovitch orbital cycles.

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Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/ science.1059412.

6.2.3.2. Modern ocean circulation

In simple terms, atmospheric and oceanic circulation systems transport excess heat from the tropics to higher latitudes—from the Equator towards the Poles. However, ocean circulation is constrained by the

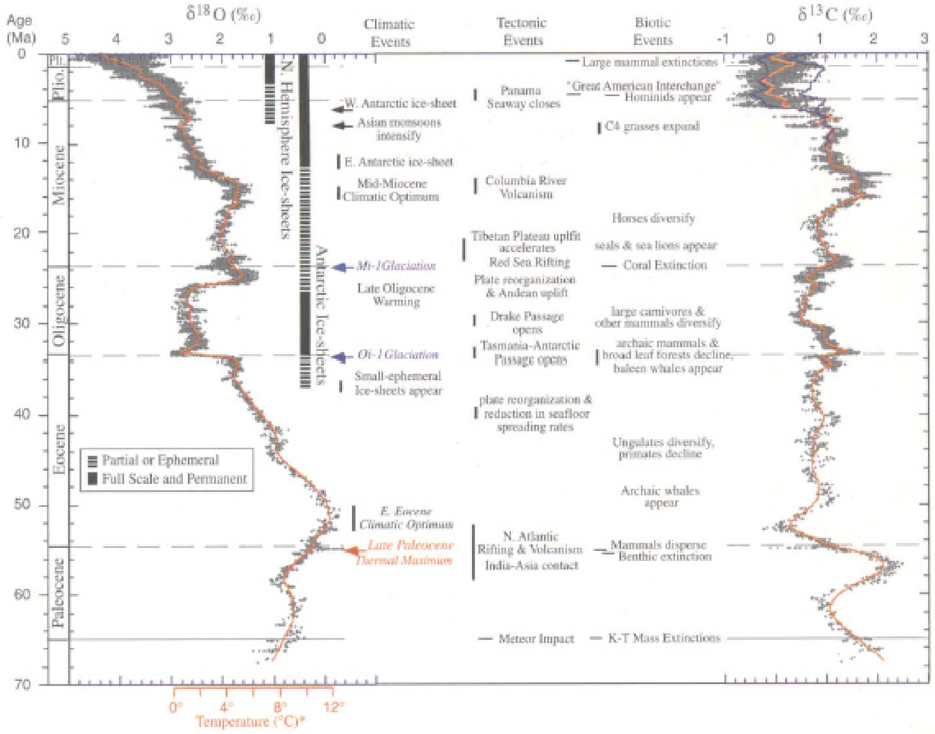

Figure 6.2.3.1.1. Summary of the major climatic, tectonic and biotic events over the last 65 million years correlated with the oxygen and carbon isotope data collected from over 40 DSDP and ODP sediment cores. Reprinted with permission from Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/science.1059412.

configurations of ocean basins and the linkages between them. As discussed in the previous section, major changes in the basin linkages in the past have been associated with significant climatic shifts (Zachos *et al.*, 2001). The current climate is, in part, a product of the modern system of ocean circulation.

There are two main components of circulation: a surface system driven primarily by wind stress exerted by the atmosphere, and a subsurface system driven primarily by density differences associated with variations in temperature and salinity (thermohaline circulation). These two systems are linked by regions where water sinks (downwelling) and rises (upwelling) to provide a complete circulation system that eventually mixes the oceans (overturning).

A popular simplification of the combined global overturning circulation is known as the Great Ocean Conveyor Belt (see Figure 6.2.3.2.1), which emphasizes the downwelling of water in the North Atlantic to drive the thermohaline circulation and the overall transport of water back into the North Atlantic by the surface circulation driving upwelling in the Indian and Pacific Oceans (Broecker, 1991). Broecker (1997) used this concept to argue global warming could trigger abrupt climate change by slowing or stopping the downwelling of water in the North Atlantic.

The flows depicted in Figure 6.2.3.2.1, however, are unrealistic: the surface heat transport in the North Pacific is in the wrong direction, and the Indonesian through-flow is exaggerated. Schmitz (1996) presented a different version of the Great Ocean Conveyor Belt summarizing the known circulation components and their volume transport rates (see Figure 6.2.3.2.2, page 805). This diagram is difficult to conceptualize, so he prepared a perspective diagram to illustrate the relationships (see Figure 6.2.3.2.3).

Although the ocean basins are linked by circulation around Antarctic and some through-flow through the Arctic and the Indonesian Archipelago, it is evident there is also significant overturning circulation within each ocean basin. Schmitz (1996) refers to this basinal circulation as consisting of meridional overturning circulation cells.

With the exception of the South Atlantic Ocean, the cells tend to involve a net transport of warm water away from the Equator at the surface and cold water towards the Equator at depth. The South Atlantic cells produce a net transport of warm water towards the Equator, adding to the transport of warm water to the North Atlantic. Overall, there is an extra 0.5 PW (petawatt = 10^{15} W) of thermal energy transported to the North Atlantic Ocean compared to the North Pacific Ocean. This extra energy is transferred to the atmosphere as latent heat though evaporation, resulting in saltier (warm) water, which sinks and drives thermohaline circulation.

To balance the water losses associated with increased evaporation in the North Atlantic, there is increased precipitation over the North Pacific,

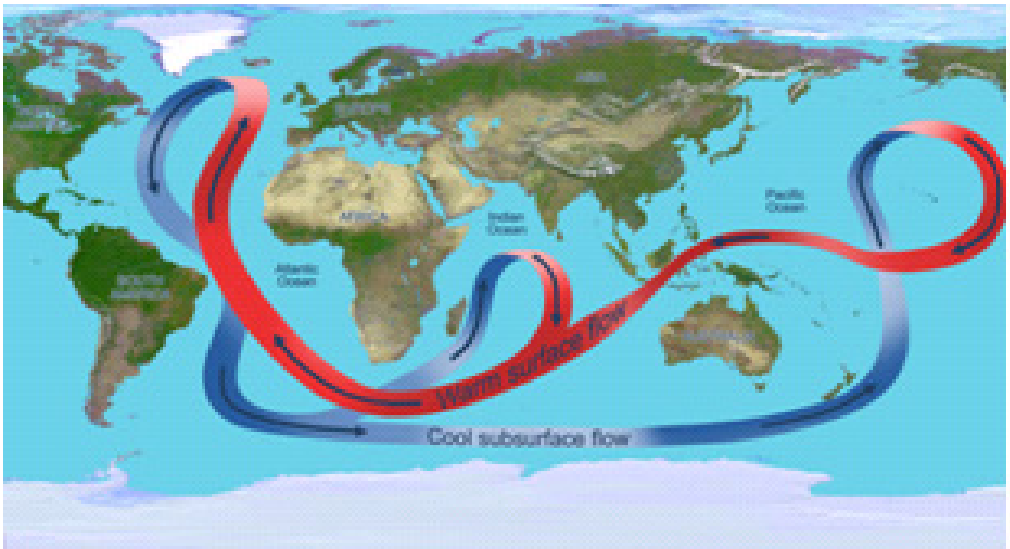

Figure 6.2.3.2.1. Simplified ocean circulation system known as the Great Ocean Conveyor Belt, highlighting the net transport of heat to the North Atlantic by surface circulation. (*http://www.jpl.nasa.gov/images/earth/ 20100325/atlantic20100325-full.jpg*).

resulting in fresher (cold) water. The component of this water that flows into the Arctic is comparatively easier to freeze than the saltier water from the North Atlantic, favoring ice formation in the Chukchi Sea over the Barents Sea.

Conclusions

Clearly, fluctuations in the supply of excess thermal energy to the North Atlantic and other oceans will have climatic consequences, and some past changes in the flow of the global ocean circulation system can be shown to be linked to major climate change; for example, flow speeds of the cold-water Pacific Deep Western Boundary Current increased during past glacial periods (Hall *et al.*, 2001). The IPCC, noting such facts, argues global warming will change the speed of major ocean circulation phenomena such as the Gulf Stream in ways that will make the world's climate less hospitable. To date, however, no published evidence exists for changes in the ocean thermohaline circulation system that lie outside the bounds of natural variation.

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6.2.3.3. Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) consists of a near-surface, warm northward flow in the Atlantic Ocean compensated by a colder southward return flow at depth (Srokosz *et al.*, 2012). A key feature is the transfer of heat to the atmosphere at high latitudes in the North Atlantic, which makes the northward-flowing surface waters saltier and cooler (denser), causing them to sink to considerable depths.

Srokosz *et al.* (2012) provide a schematic illustration of the main flows of AMOC (see Figure 6.2.3.3.1, page 806). Similar to the Great Ocean Conveyor Belt, this schematic oversimplifies the components of the circulation cell. Figure 6.2.3.3.2

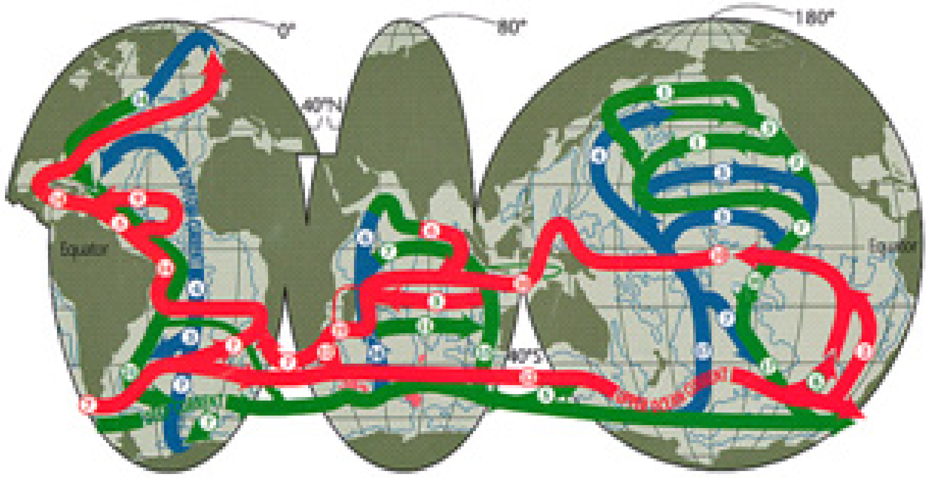

Figure 6.2.3.2.2. Summary of the main components of global ocean circulation. The volume transport rates in Sverdrups (1 Sv = 106 m^3.s^{-1}) are indicated in the circles. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

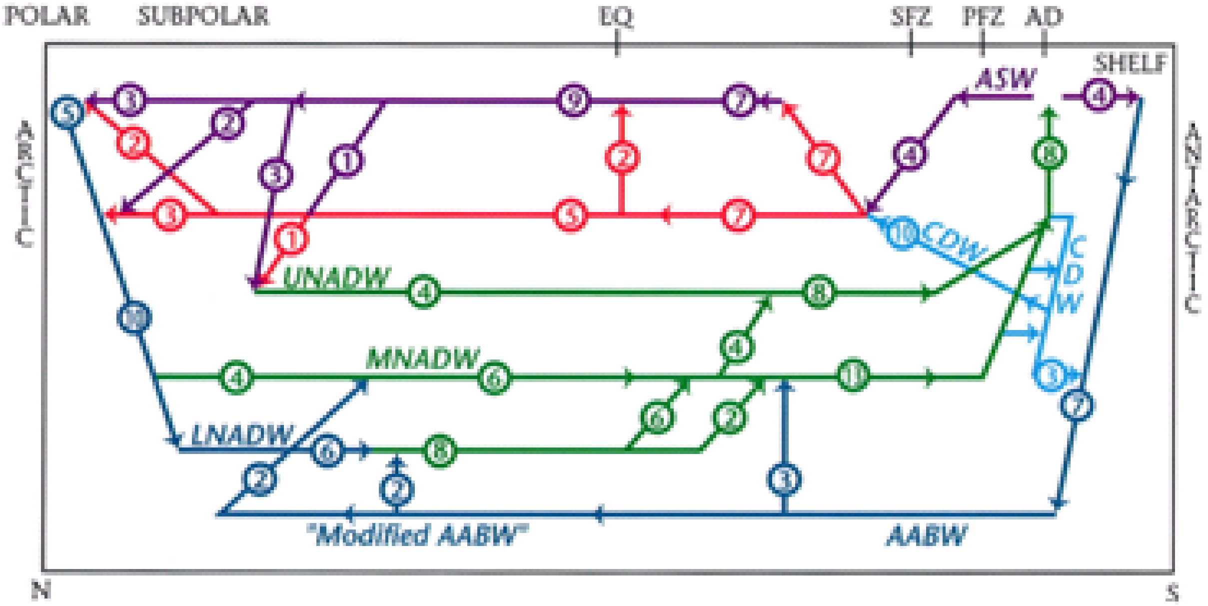

Figure 6.2.3.2.3. Components of AMOC at different depths within the Atlantic, where purple denotes an upper layer, red indicates intermediate water, green deep water, dark blue bottom, and light blue represents Circumpolar Deep Water (Schmitz, 1996). The volume transport rates for each limb are given in Sverdrups.

(on page 807), originally presented by Schmitz (1996), summarizes the major components of the circulation contributing to AMOC. This figure illustrates the deeper thermohaline circulation is also driven by water sinking around Antarctica, which means the strength of the circulation is not solely a function of the formation of dense water in the North Atlantic. There are multiple flow paths at different depths, meaning there are many different lags associated with the circulation of water masses within the system.

Baehr *et al.* (2007, 2008) used modeling to

Figure 6.2.3.3.1. Simplified model of the AMOC that regulates northern Hemisphere climate. Reprinted with permission from Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delworth, T., Lozier, S., Marotzke, J., and Sutton, R. 2012. Past, present, and future changes in the Atlantic Meridional Overturning Circulation. *Bulletin of the American Meteorological Society* **93**(11): 1663–1676. doi:10.1175/ BAMS-D-11-00151.1.

assess how quickly changes in the North Atlantic meridional overturning circulation (MOC) might flow through into consequential climate change. Simulated observations were projected onto a time-independent spatial pattern of natural variability. This variability was derived by regressing the zonal density gradient along 26°N against the strength of the MOC at 26°N, within a model-based control climate simulation. The resultant pattern was compared against observed anomalies found between the 1957 and 2004 hydrographic occupations of this latitudinal section.

The modeling revealed Atlantic MOC changes could be detected with 95% reliability after about 30 years, manifest by changes in zonal density gradients obtained from a recently deployed monitoring array. In terms of potential past changes Baehr *et al.* found "for the five hydrographic occupations of the 26°N transect, none of the analyzed depth ranges shows a significant trend between 1957 and 2004, implying that there was no MOC trend over the past 50 years."

This finding demonstrates the mild late twentieth century warming that so alarms the IPCC has not resulted in any observable change in the North Atlantic MOC. In turn, this suggests the North Atlantic MOC is not nearly as sensitive to global warming as many climate models employed by the IPCC suggest.

In a second paper addressing North Atlantic deep water formation and circulation, Vage *et al.* (2008) write, "in response to global warming, most climate models predict a decline in the Meridional Overturning Circulation, often due to a reduction of Labrador Sea Water," noting "since the mid-1990s, convection in the Labrador Sea has been shallow—and at times nearly absent."

Vage *et al.*'s paper uses Argo data, supplemented by satellite and reanalysis data, to document a return of deep convection to the subpolar gyre in both the Labrador and Irminger seas in the winter of 2007–2008. Winter mixing was observed to depths of 1,800 m in the Labrador Sea, 1,000 m in the Irminger Sea, and 1,600 m south of Greenland, whereas base-period (the winters of 2001–2006) mixing depths were less than 1,000 m. By analyzing heat flux components, Vage *et al.* determined the main cause of the enhanced heat flux and deep mixing was unusually cold air temperatures during the 2007–2008 winter. Moreover, the cooling was not merely a local phenomenon; global temperature dropped 0.45°C between the winters of 2006–2007 and 2007–2008.

Srokosz *et al.* (2012) provide a review of available research on AMOC and associated climatic variations. They highlight how poorly understood the system is; the lack of key time series data, particularly for the deeper components of AMOC; and the poor predictive abilities of computer models. From the available data, they demonstrate the recent behavior of AMOC has been surprising and unexplainable. They conclude AMOC plays a major role in climate changes, there is an urgent need for better observational data, and the behavior and potential predictability of the system need further study.

Conclusions

Studies of various parts of the global thermohaline circulation show flow rates can be quite widely variable. This variability has natural causes that have yet to be identified fully. Meanwhile, no evidence exists for additional change in ocean circulation forced by human carbon dioxide emissions.

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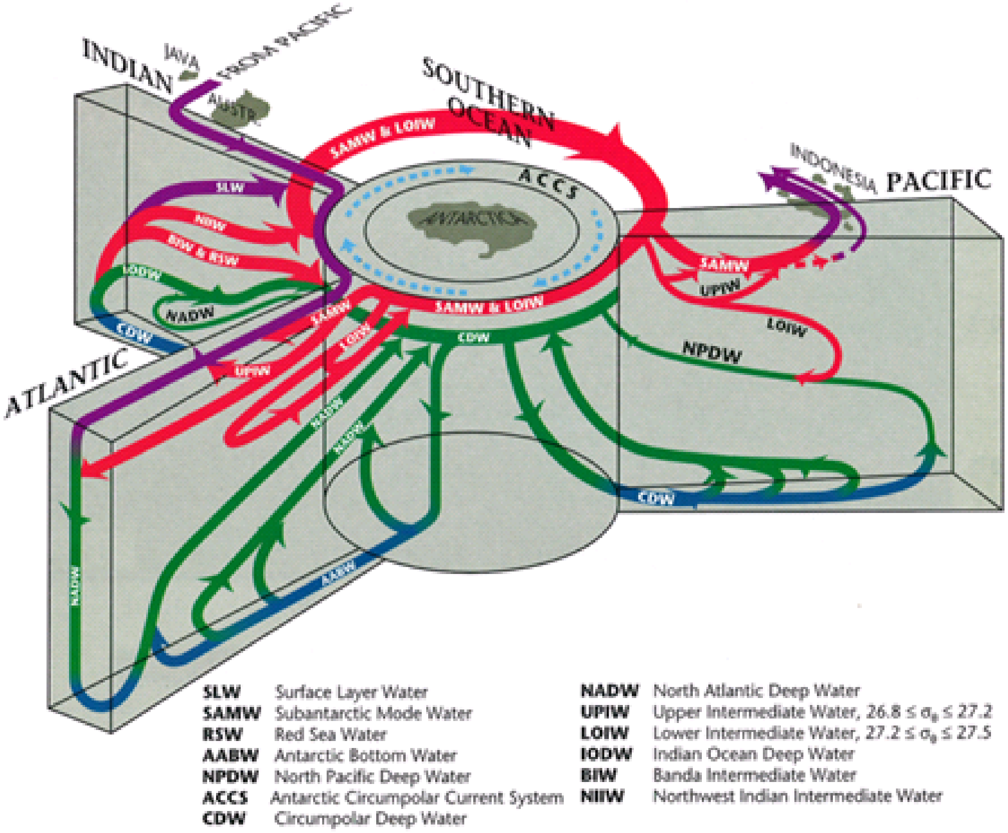

Figure 6.2.3.3.2. Summary of the main components of the global ocean circulation system. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

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