3

Solar Forcing of Climate

Willie Soon (USA)

Sebastian Lüning (Germany)

Key Findings

Introduction

3.1 Solar Irradiance
3.2 Cosmic Rays
3.3 Temperature
  3.3.1 Global
  3.3.2 Northern Hemisphere
  3.3.3 North America
  3.3.4 South America
  3.3.5 Asia
  3.3.6 Europe
  3.3.7 Other Geographical Regions
3.4 Precipitation
  3.4.1 North America
  3.4.2 South America
  3.4.3 Africa
  3.4.4 Asia and Australia
  3.4.5 Europe
3.5 Other Climatic Variables
  3.5.1 Droughts
  3.5.2 Floods
  3.5.3 Monsoons
  3.5.4 Streamflow
3.6 Future Influences

Key Findings

The following points summarize the main findings of this chapter:

- Evidence is accruing that changes in Earth's surface temperature are largely driven by variations in solar activity. Examples of solar-controlled climate change epochs include the Medieval Warm Period, Little Ice Age and Early Twentieth Century (1910–1940) Warm Period.

- The Sun may have contributed as much as 66% of the observed twentieth century warming, and perhaps more.

- Strong empirical correlations have been reported from all around the world between solar variability and climate indices including temperature, precipitation, droughts, floods, streamflow, and monsoons.

- IPCC models do not incorporate important solar factors such as fluctuations in magnetic intensity and overestimate the role of human-related CO_2 forcing.

- The IPCC fails to consider the importance of the demonstrated empirical relationship between solar activity, the ingress of galactic cosmic rays, and the formation of low clouds.

- The respective importance of the Sun and CO_2 in forcing Earth climate remains unresolved; current climate models fail to account for a plethora of known Sun-climate connections.

- The recently quiet Sun and extrapolation of solar cycle patterns into the future suggest a planetary cooling may occur over the next few decades.

Introduction

The 2007 *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) claims "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations [italics in the original]" (IPCC, 2007-I, p. 10). The authors go so far as to suggest there is a better-than-90-percent probability their assessment is true. Similar assertions are made in the IPCC's forthcoming *Fifth Assessment Report* (AR5), which concludes "CO_2 is the strongest driver of climate change compared to other changes in the atmospheric composition, and changes in surface conditions. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers" (p. 7 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). But as demonstrated in Chapter 1 of this report, the global climate models upon which the IPCC rests its case are notoriously unreliable.

Chapter 2 documented feedback factors and forcings the IPCC has downplayed or overlooked, and Chapters 4–7 will show that real-world climate observations do not confirm the trends the IPCC claims should exist if its theory of CO_2-dominated climate change were true. This chapter explores an alternative theory of climate change the IPCC has rejected: that the *Sun's* influence likely played the more dominant role in Earth's climate over the past century and beyond.

The following statements taken from the Second Order Draft (SOD) of AR5 illustrate the IPCC's rejection of the Sun's influence as a major factor in contemporary climate change:

> Changes in the astronomical alignment of the Sun and Earth induce cyclical changes in radiative forcing, but this is substantial only at millennial and longer timescales. (p. 8.30, SOD)
>
> Quantification of the contributions of anthropogenic and natural forcing using multi-signal detection and attribution analyses show it is extremely likely that human activities (with very high confidence) have caused most (at least 50%) of the observed increase in global average temperatures since 1951. Detection and attribution analyses show that the greenhouse gas warming contribution of 0.6°C–1.4°C was very likely greater than the observed warming of 0.6°C over the period 1951–2010. The response to aerosols and other anthropogenic forcings appears to be less clearly detectable using CMIP5 models than it was using CMIP3 models, but they probably contributed a net cooling over this period (Figure TS.8). Such analyses also indicate a trend of less than 0.1°C was attributable to combined forcing from solar irradiance variations and volcanic eruptions over this period. Taken together with other evidence this indicates that it is extremely unlikely that the contribution from solar forcing to the warming since 1950 was larger than that from greenhouse gases. Better understanding of pre-instrumental data shows that observed warming over this period is far outside the range of internal climate variability estimated from such records, and it is also far outside the range of variability simulated in climate models. Based on the surface temperature record, we therefore assess that it is virtually certain that warming since 1950 cannot be explained by internal variability alone. (p.23 of the Technical Summary, SOD)

Much of the IPCC's examination of the possible influence of the Sun on Earth's climate begins and ends with a discussion of total solar irradiance (TSI). According to the IPCC, secular trends in TSI are too small—estimated at only +0.04 [-0.01 to +0.09] W m^{-2} since 1750—to have had much of an influence on the rising temperatures of the Current Warm Period. But as the material in this chapter shows, the IPCC is likely vastly underestimating this influence.

One possible reason, according to Soon *et al.* (2011), may rest in the fact that the low-amplitude TSI reconstruction estimates utilized by the IPCC and others (e.g., Lean *et al*., 2005) are based on computer modeling by Wang *et al.* (2005), whose magnetic flux transport model "was not designed to model irradiance changes or to assess the solar energy budget." In addition, Soon *et al.* note Wang *et al.*'s model "does not even contain a radiative transfer routine, which is essential to a proper description of solar physics" leaving Soon *et al.* to conclude "the Lean *et al*. (2005) reconstruction [used by the IPCC] is limited in its ability to describe variations in TSI." Additional discussion of the reconstruction of the TSI history can be found in pp. 46–47 of Soon and Legates (2013).

A second reason the IPCC fails to acknowledge a significant solar influence on recent climate is that it is looking for evidence (or rather a lack thereof) in the wrong places. Determining the correct or proper climatic metric to discern a solar-climate link may not be not as straightforward as it would seem. From Lindzen (1994) to Karamperidou *et al.* (2012), for example, it has been proposed that perhaps the most relevant variable for studying how climate varies is the so-called Equator-to-Pole temperature gradient (EPTG) (traditionally, the Northern Hemisphere record is considered because the data coverage over the Southern Hemisphere is sparse and less reliable), not near-surface air temperatures, which Lindzen (1994) interpreted to be simply a residual product of the change in EPTG rather than the other way around.

Figure 3.1 illustrates the value of plotting TSI values with the Northern Hemisphere EPTG data. As indicated in the left panel of the figure, the close correlation between the data demonstrates the Sun's role in climate should not be discounted or outright dismissed, illustrating the potentially dominant role of the TSI in modulating climate on timescales of multiple decades to a century. A much weaker correlation is seen in the right panel of the figure, which displays atmospheric CO_2 data in the place of TSI, suggesting a much more tenuous and implausible relationship between atmospheric CO_2 and climate.

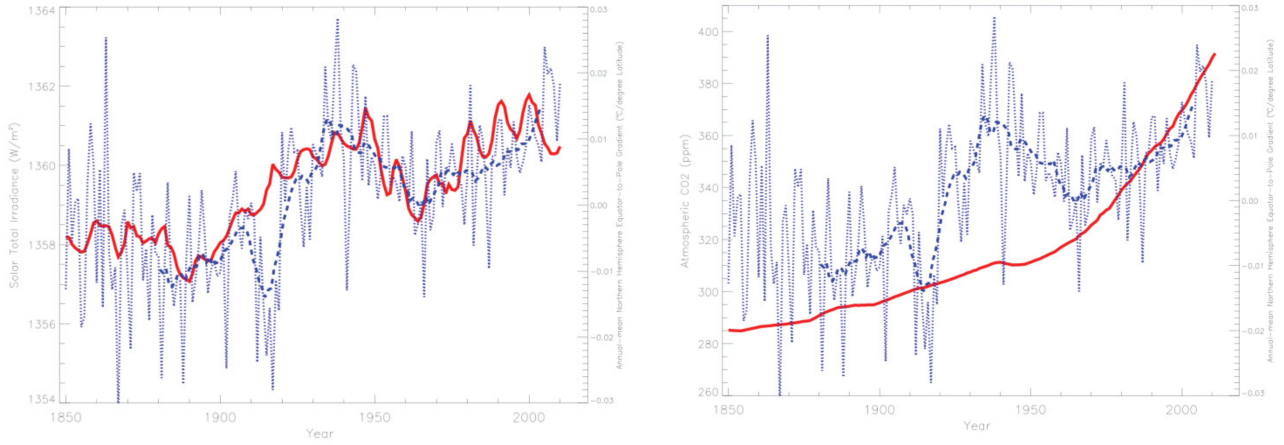

Figure 3.1. A comparison and contrast of the modulation of the Northern-Hemispheric equator-to-pole temperature gradient (both panels, dotted blue curves) by Total Solar Irradiance (TSI, left panel, solid red line) and by atmospheric CO_2 (right panel, solid red line). Adapted from Soon, W. and Legates, D.R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics* **93**: 45–56.

Throughout this chapter we examine evidence for an alternative theory of climate change: That variations in the Sun's radiation output and magnetic field, mediated by cosmic ray fluxes and changes in global cloud cover, play a larger role in regulating Earth's temperature, precipitation, droughts, floods, monsoons, and other climate features than any past or expected human activities, including projected increases in greenhouse gas (GHG) emissions. We also discuss another mechanism involving the ultraviolet (UV) component of solar radiation, which fluctuates much more intensely than the visible light. The UV changes are known to cause significant changes in the stratosphere, affecting ozone, and recent studies suggest these effects may propagate down into the lower atmosphere through complex physical and chemical interactions.

We begin by analzing research on solar irradiance, followed by an in-depth discussion of the cosmic ray theory of climate forcing. We then review empirical evidence linking solar variability to climate phenomena in both ancient and modern times. Establishing this latter fact is important because regardless of the mechanism(s) involved, the fact that such tightly coupled relationships exist in nature supports the thesis that relatively small fluctuations in solar output can indeed produce significant changes in climate.

References

IPCC. 2007-I. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Cambridge University Press, Cambridge, UK.

Karamperidou, C., Cioffi, F., and Lall, U. 2012. Surface temperature gradients as diagnostic indicators of mid-latitude circulation dynamics. *Journal of Climate* **25**: 4154–4171.

Lean, J., Rottman, G., Harder, J., and Kopp, G. 2005. SORCE contributions to new understanding of global change and solar variability. *Solar Physics* **230**, 27−53.

Lindzen, R.S. 1994. Climate dynamics and global change. *Annual Review of Fluid Mechanics* **26**: 353–378.

Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 2331–2344.

Soon, W. and Legates, D.R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics* **93**: 45–56.

Wang, Y.M., Lean, J.L., and Sheeley, N.R. 2005. Modeling the sun's magnetic field and irradiance since 1713. *The Astrophysical Journal* **625**: 522−538.

3.1 Solar Irradiance

Changes in solar irradiance and ultraviolet radiation may yield a much larger influence on global climate than that envisioned by the IPCC to result from rising atmospheric CO_2 (see, for example, Soon *et al.* 2000). The often-used comparison of the *relative* radiative forcing of the Sun's irradiance versus rising atmospheric CO_2, as popularized in the IPCC reports, misses important physical insights.

In evaluating the overall significance of solar vs. CO_2 forcings, an apples-to-apples comparison would be to contrast the role of these two parameters on an *absolute* scale. For incoming solar radiation, the absolute forcing amounts to around 340 W m^{-2} at the top of the atmosphere. The absolute forcing of atmospheric CO_2 is estimated at about 32-34 W m^{-2} (see pp. 202–203 of Kiehl and Trenberth 1997). (A recent publication by Huang [2013, p. 1707], however, has calculated this value may be as high as 44.1 W m^{-2}.) Small changes in the absolute forcing of the Sun can easily result in values much larger than the predicted changes in radiative forcing typically associated with increasing CO_2, and these forcings could easily influence Earth's climate.

Evidence for a much stronger relationship between the Sun and Earth's climate than that envisioned by the IPCC is seen in many empirical studies. Karlén (1998), for example, examined proxy climate data related to changes in summer temperatures in Scandinavia over the past 10,000 years. This temperature record—derived from analyses of changes in the size of glaciers, changes in the altitude of the alpine tree-limit, and variations in the width of annual tree rings—was compared with contemporaneous solar irradiance data derived from ^{14}C anomalies measured in tree rings. The record revealed both long- and short-term temperature fluctuations found to be "closely related" to the ^{14}C-derived changes in solar irradiation, leading Karlén to conclude "the similarity between solar irradiation changes and climate indicate a solar influence on the Scandinavian and Greenland climates." He further concluded "the frequency and magnitude of changes in climate during the Holocene [i.e., the current interglacial] do not support the opinion that the climatic change of the last 100 years is unique," bluntly adding "there is no evidence of a human influence so far."

Also writing just before the turn of the century, Lockwood *et al.* (1999) analyzed measurements of the near-Earth interplanetary magnetic field to determine the total magnetic flux leaving the Sun since 1868. Their analysis showed the total flux rose by a factor of 1.41 over the 32-year period 1964–1996, whereas surrogate measurements of the interplanetary magnetic field previous to this time indicated the total flux had increased by a factor of 2.3 since 1901. These findings and others linking changes in solar magnetic activity with terrestrial climate change led the authors to state "the variation [in the total solar magnetic flux] found here stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field."

Parker (1999) noted the number of sunspots also roughly doubled since 1901, and one consequence of this phenomenon is a much more vigorous and slightly brighter Sun. Parker also drew attention to the fact that NASA spacecraft measurements had revealed the brightness (Br) of the Sun varies by the "change in $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle." During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth-century Medieval Maximum), he pointed out, brightness variations on the order of change in ΔBr/Br ≈ 0.5% typically occur (see Zhang *et al.* 1994, based on observational constraints from solar-type stars, for empirical support for the possibility of such a large-amplitude change). He noted the mean temperature (T) of the northern portion of Earth varied by 1 to 2°C in association with these variations in solar activity, stating, "we cannot help noting that ΔT/T ≈ ΔBr/Br."

Also in 1999, Chambers *et al.* (1999) noted research findings in both palaeoecology and solar science "indicate a greater role for solar forcing in Holocene climate change than has previously been recognized." They found substantial evidence within the Holocene for solar-driven variations in Earth-atmosphere processes over a range of timescales stretching from the 11-year solar cycle to century-scale events. They acknowledge the absolute solar flux variations associated with these phenomena are rather small, but they identify a number of "multiplier effects" that can operate on solar rhythms in such a way that "minor variations in solar activity can be reflected in more significant variations within the Earth's atmosphere."

The three researchers also noted nonlinear responses to solar variability are inadequately represented in (in fact, essentially ignored by) the global climate models used by the IPCC to predict future CO_2-induced global warming, while at the same time other amplifier effects are used to model the hypothesized CO_2-induced global warming of the future, where CO_2 is only an initial perturber of the climate system which, according to the IPCC, sets other more powerful forces in motion that produce the bulk of the warming.

Bard *et al.* (2000) identified some of the many types of information that have been used to reconstruct past solar variability, including "the envelope of the SSN [sunspot number] 11-year cycle (Reid, 1991), the length and decay rate of the solar cycle (Hoyt and Schatten, 1993), the structure and decay rate of individual sunspots (Hoyt and Schatten, 1993), the mean level of SSN (Hoyt and Schatten, 1993; Zhang *et al.*, 1994; Reid, 1997), the solar rotation and the solar diameter (Nesme-Ribes *et al.*, 1993), and the geomagnetic aa index (Cliver *et al.*, 1998)." They also noted "Lean *et al.* (1995) proposed that the irradiance record could be divided into 2 superimposed components: an 11-year cycle based on the parameterization of sunspot darkening and facular brightening (Lean *et al.*, 1992), and a slowly varying background derived separately from studies of Sun-like stars (Baliunas and Jastrow, 1990)," and that Solanki and Fligge (1998) had developed an even more convoluted technique.

Bard *et al.* used an entirely different approach. Rather than directly characterize some aspect of solar variability, they assessed certain consequences of that variability. Specifically, they noted magnetic fields of the solar wind deflect portions of the primary flux of charged cosmic particles in the vicinity of Earth, leading to reductions in the creation of cosmogenic nuclides in Earth's atmosphere. Consequently, they reasoned histories of the atmospheric concentrations of ^{14}C and ^{10}Be can be used as proxies for solar activity, as noted many years earlier by Lal and Peters (1967).

In employing this approach to the problem, the four researchers first created a 1,200-year history of cosmonuclide production in Earth's atmosphere from ^{10}Be measurements of South Pole ice (Raisbeck *et al.*, 1990) and the atmospheric $^{14}C/^{12}C$ record as measured in tree rings (Bard *et al.*, 1997). This record was converted to total solar irradiance (TSI) values by "applying a linear scaling using the TSI values published previously for the Maunder Minimum," when cosmonuclide production was 30 to 50 percent above the modern value. This process resulted in an extended TSI record suggesting, in their words, that "solar output was significantly reduced between AD 1450 and 1850, but slightly higher or similar to the present value during a period centered around AD 1200." "It could thus be argued," they say, "that irradiance variations may have contributed to the so-called 'little ice age' and 'medieval warm period.'"

But Bard *et al.* downplay their own suggestion, because, as they report, "some researchers have concluded that the 'little ice age' and/or 'medieval warm period' [were] regional, rather than global events." Noting the TSI variations they developed from their cosmonuclide data "would tend to force global effects," they concluded they could not associate this global impetus for climate change with what other people were calling regional climatic anomalies. (Chapter 4 of this report demonstrates the Little Ice Age and Medieval Warm Period were in fact global in extent.)

Updated discussions of the complexity and physics involved in the reconstruction of the TSI are found in the work of Fontenla *et al.* (2011), Shapiro *et al.* (2011), and section 2 of Soon and Legates (2013). It is important to contrast these in-depth studies with other TSI reconstruction studies used by the IPCC, which are based on rather questionable statistical correlations: See, for example, equation 4 in

Steinhilber *et al.* (2009), where the inter-calibration, originally published in Figure 4c of Frohlich (2009), between TSI and the so-called open magnetic field strength was based on only three data points.

Rozelot (2001) conducted a series of analyses designed to determine whether phenomena related to variations in the radius of the Sun may have influenced Earth's climate over the past four centuries. He found "at least over the last four centuries, warm periods on the Earth correlate well with smaller apparent diameter of the Sun and colder ones with a bigger Sun." Although the results of this study were correlative and did not identify a physical mechanism capable of inducing significant climate change on Earth, Rozelot reports the changes in the Sun's radius are "of such magnitude that significant effects on the Earth's climate are possible."

Rigozo *et al.* (2001) created a history of sunspot numbers for the past 1,000 years "using a sum of sine waves derived from spectral analysis of the time series of sunspot number R_Z for the period 1700–1999," and from this record they derived the strengths of parameters related to aspects of solar variability. The researchers state "the 1000-year reconstructed sunspot number reproduces well the great maximums and minimums in solar activity, identified in cosmonuclides variation records, and, specifically, the epochs of the Oort, Wolf, Sporer, Maunder, and Dalton Minimums, as well [as] the Medieval and Modern Maximums," the last of which they describe as "starting near 1900."

The mean sunspot number for the Wolf, Sporer, and Maunder Minimums was 1.36. For the Oort and Dalton Minimums it was 25.05; for the Medieval Maximum it was 53.00; and for the Modern Maximum it was 57.54. Compared with the average of the Wolf, Sporer, and Maunder Minimums, therefore, the mean sunspot number of the Oort and Dalton Minimums was 18.42 times greater; that of the Medieval Maximum was 38.97 times greater; and that of the Modern Maximum was 42.31 times greater. Similar strength ratios for the solar radio flux were 1.41, 1.89, and 1.97, respectively. For the solar wind velocity the corresponding ratios were 1.05, 1.10, and 1.11, and for the southward component of the interplanetary magnetic field they were 1.70, 2.54, and 2.67.

Both the Medieval and Modern Maximums in sunspot number and solar variability parameters stand out above all other periods of the past thousand years, with the Modern Maximum slightly besting the Medieval Maximum. These authors from Brazil and Puerto Rico recently updated (see Echer *et al.* 2012) their analysis using NASA Goddard Institute for Space Studies temperature records and found a stronger statistical correlation of the surface temperature with the sunspot number data record in the 22-year Hale magnetic cycle band, with lags from zero to four years, than in the correlation in the 11-year solar cycle band.

Noting several spacecraft have monitored total solar irradiance (TSI) for the past 23 years, with at least two of them operating simultaneously at all times, and that TSI measurements made from balloons and rockets supplement the satellite data, Frohlich and Lean (2002) compared the composite TSI record with an empirical model of TSI variations based on known magnetic sources of irradiance variability, such as sunspot darkening and brightening, after which they described how "the TSI record may be extrapolated back to the seventeenth century Maunder Minimum of anomalously lower solar activity, which coincided with the coldest period of the Little Ice Age." This exercise "enables an assessment of the extent of post-industrial climate change that may be attributable to a varying Sun, and how much the Sun might influence future climate change."

Frohlich and Lean state "warming since 1650 due to the solar change is close to 0.4°C, with pre-industrial fluctuations of 0.2°C that are seen also to be present in the temperature reconstructions." It would appear solar variability can explain a significant portion of the warming of Earth in recovering from the global chill of the Little Ice Age. With respect to the future, the two solar scientists state, "solar forcing is unlikely to compensate for the expected forcing due to the increase of anthropogenic greenhouse gases which are projected to be about a factor of 3–6 larger." The magnitude of that anthropogenic forcing, however, has been computed by many different approaches to be much smaller than the value employed by Frohlich and Lean in making this comparison (Idso, 1998).

Douglass and Clader (2002) used multiple regression analysis to separate surface and atmospheric temperature responses to solar irradiance variations over the past two-and-a-half solar cycles (1979–2001) from temperature responses produced by variations in ENSO and volcanic activity. Based on the satellite-derived lower tropospheric temperature record, they evaluated the sensitivity (*k*) of temperature (T) to solar irradiance (I), where temperature sensitivity to solar irradiance is defined as $k = \Delta T/\Delta I$, obtaining the result of $k = 0.11 \pm 0.02°C/(W/m^2)$. Similar analyses based on the radiosonde temperature record of Parker *et al*. (1997) and the surface air temperature records of Jones *et al*. (2001) and Hansen and Lebedeff (1987, with updates) produced *k* values of 0.13, 0.09, and $0.11°C/(W/m^2)$, respectively, with the identical standard error of $\pm 0.02°C/(W/m^2)$. In addition, they reported White *et al*. (1997) derived a decadal timescale solar sensitivity of $0.10 \pm 0.02°C/(W/m^2)$ from a study of upper ocean temperatures over the period 1955–1994 and Lean and Rind (1998) derived a value of $0.12 \pm 0.02°C/(W/m^2)$ from a reconstructed paleo-temperature record spanning the period 1610–1800.

Douglass and Clader concluded, "the close agreement of these various independent values with our value of 0.11 ± 0.02 [$°C/(W/m^2)$] suggests that the sensitivity *k* is the same for both decadal and centennial time scales and for both ocean and lower tropospheric temperatures." They further suggest if these values of *k* hold true for centennial time scales, which appears to be the case, their high-end value implies a surface warming of 0.2°C over the past 100 years in response to the 1.5 W/m^2 increase in solar irradiance inferred by Lean (2000) for this period. This warming represents approximately one-third of the total increase in global surface air temperature estimated by Parker *et al*. (1997), 0.55°C, and Hansen *et al*. (1999), 0.65°C, for the same period. It does not, however, include potential indirect effects of more esoteric solar climate-affecting phenomena, such as those from cosmic rays as discussed in Section 3.2 of this chapter, that also could have been operative over this period.

Foukal (2002) analyzed the findings of space-borne radiometry and reported "variations in total solar irradiance, S, measured over the past 22 years, are found to be closely proportional to the difference in projected areas of dark sunspots, AS, and of bright magnetic plage elements, APN, in active regions and in enhanced network." They also found "this difference varies from cycle to cycle and is not simply related to cycle amplitude itself," which suggests there is "little reason to expect that S will track any of the familiar indices of solar activity." On the other hand, he notes, "empirical modeling of spectro-radiometric observations indicates that the variability of solar ultraviolet flux, FUV, at wavelengths shorter than approximately 250 nm, is determined mainly by APN alone."

Using daily data from the Mt. Wilson Observatory covering the period 1905–1984 and partially overlapping data from the Sacramento Peak Observatory that extended through 1999, Foukal derived time series of total solar and UV irradiances between 1915 and 1999, which he then compared with global temperature data for that period. He reported, "correlation of our time series of UV irradiance with global temperature, T, accounts for only 20% of the global temperature variance during the 20th century" but "correlation of our total irradiance time series with T accounts statistically for 80% of the variance in global temperature over that period."

The UV findings of Foukal were not impressive, but the results of his total solar irradiance analysis were, leading him to state "the possibility of significant driving of twentieth century climate by total irradiance variation cannot be dismissed." Although the magnitude of the total solar effect was determined to be "a factor 3–5 lower than expected to produce a significant global warming contribution based on present-day climate model sensitivities," what Foukal calls the "high correlation between S and T" strongly suggests changes in S largely determine changes in T, confirmation of which likely awaits only what he refers to as an "improved understanding of possible climate sensitivity to relatively small total irradiance variation."

Willson and Mordvinov (2003) analyzed total solar irradiance (TSI) data obtained from different satellite platforms over the period 1978–2002, attempting to resolve various small but important inconsistencies among them. In doing so, they recongized "construction of TSI composite databases will not be without its controversies for the foreseeable future." Nevertheless, their most interesting result, in the estimation of the two researchers, was their confirmation of a +0.05%/decade trend between the minima separating solar cycles 21–22 and 22–23, which they say "appears to be significant."

Willson and Mordvinov say the finding of the 0.05 percent/decade minimum-to-minimum trend "means that TSI variability can be caused by unknown mechanisms other than the solar magnetic activity cycle," which means "much longer time scales for TSI variations are therefore a possibility," which they say "has obvious implications for solar forcing of climate." Undiscovered long-term variations in total solar irradiance could explain centennial-scale climate variability, which Bond *et al*. (2001) already have demonstrated to be related to solar activity, as well as the millennial-scale climatic oscillation that pervades both glacial and interglacial periods (Oppo *et al*., 1998; Raymo *et al*., 1998).

Like Willson and Mordvinov, Foukal (2003) acknowledged "recent evidence from ocean and ice cores suggests that a significant fraction of the variability in northern hemisphere climate since the last Ice Age correlates with solar activity (Bond *et al*., 2001)," while noting "a recent reconstruction of S [total solar irradiance] from archival images of spots and faculae obtained daily from the Mt. Wilson Observatory in California since 1915 shows remarkable agreement with smoothed global temperature in the 20th century," citing his own work of 2002. He acknowledged the observed variations in S between 1978 and 2002 were not large enough to explain the observed temperature changes on Earth within the context of normal radiative forcing and proceeded to consider the status of research into subjects that might explain this situation. He reviewed then-current knowledge relative to the idea that "the solar impact on climate might be driven by other variable solar outputs of ultraviolet radiation or plasmas and fields via more complex mechanisms than direct forcing of tropospheric temperature" and concluded, "we cannot rule out multi-decadal variations in S sufficiently large to influence climate, yet overlooked so far through limited sensitivity and time span of our present observational techniques."

Citing the work of Herman and Goldberg (1978), Pittock (1983), Hoyt and Schatten (1997), and van Loon and Labitzke (2000), Thejll *et al*. (2003) note "apparent relations between solar activity, or parameters closely related to solar activity, and climate data have often been reported." Noting further that a substantial portion of Northern Hemispheric climate variability is associated with the North Atlantic Oscillation (NAO), as described by Hurrell *et al*. (2001), they report the activity of the NAO has been found to be related to solar-geomagnetic parameters (Bucha and Bucha, 1998; Boberg and Lundstedt, 2002; Kodera, 2002).

Thejll *et al*. examined spatial and temporal relationships among the geomagnetic index (*Ap*), the NAO, stratospheric geopotential height, and sea level pressure, revealing "significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000," but "for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere." By using "Monte Carlo simulations of the statistical procedures applied to suitable surrogate data," they also concluded these correlations are due to the existence of a "real physical link." They also noted in the 1973–2000 period only the winter season series are significantly correlated, which they say "is consistent with the notion that the solar-climate link works through the stratosphere."

Thejll *et al.* stated their findings may be explained in two different ways: either the influence of the Sun increased through time, reaching a strong enough level in the 1970s to make the correlations they studied become statistically significant, or the state of the atmosphere changed in the 1970s, becoming more sensitive to the solar influence than it had been. Their findings strengthen the case for solar-induced perturbations being propagated downward from the stratosphere to the troposphere (Hartley *et al*., 1998; Carslaw *et al*., 2002).

Ineson *et al.* (2011) modeled the effects of realistic solar UV (200–320 nm) irradiance changes between solar activity minima and maxima in the stratosphere and mesosphere, finding weaker westerly winds during the winters with a less active Sun that may drive cold winters in Northern Europe and the United States and mild winters over Southern Europe and Canada, as observed in recent years. The observational analyses by Hood *et al.* (2013) add insight into the specific regional patterns of the near-surface responses that likely originated from the solar UV forcing of ozone and related wind-thermal fields in the stratosphere. These authors note "the observational analyses … provide additional evidence that a surface climate response to 11-yr solar forcing during the boreal winter season is detectable in global SLP and SST records extending back to the 19th century. The response is most clearly detected in the Pacific sector where a positive solar SLP response anomaly is obtained over the Aleutian region and a corresponding positive SST response anomaly extends across the midlatitude North Pacific ... The SLP response in the Arctic is generally negative supporting the hypothesis that the solar response is similar to a positive Arctic Oscillation mode. However, only a weak and marginally significant SST response is obtained in the equatorial eastern Pacific so the response differs from that which characterizes a La Niña event ... Analyses of the observed response as a function of phase lag indicate that the solar SLP response evolves from a predominately negative AO structure a few years prior to solar maximum to a predominately positive AO structure at and following solar maximum. ... The amplitudes of the Aleutian SLP response anomaly and the corresponding positive

SST anomaly maximize at zero lag."

As Hood *et al.* (2013) declared, "in general, models should be validated by observations rather than the other way around."

To be sure, some of the Sun-climate relation studies have been challenged. In 2004, Damon and Laut (2004) reported what they described as errors made by Friis-Christensen and Lassen (1991), Svensmark and Friis-Christensen (1997), Svensmark (1998), and Lassen and Friis-Christensen (2000) in their presentation of solar activity data correlated with terrestrial temperature data. The Danish scientists' error, in the words of Damon and Laut, was "adding to a heavily smoothed ('filtered') curve, four additional points covering the period of global warming, which were only partially filtered or not filtered at all." This in turn led to an apparent dramatic increase in solar activity over the last quarter of the twentieth century that closely matched the equally dramatic rise in temperature manifest by the Northern Hemispheric temperature reconstruction of Mann *et al.* (1998, 1999) over the same period. With the acquisition of additional solar activity data in subsequent years, however, and with what Damon and Laut called the proper handling of the numbers, the late twentieth century dramatic increase in solar activity disappears.

This new result, to quote Damon and Laut, means "the sensational agreement with the recent global warming, which drew worldwide attention, has totally disappeared." In reality, however, it is only the agreement with the last quarter-century of the discredited Mann *et al.* "hockey stick" temperature history that has disappeared. This new disagreement is important, for the Mann *et al.* temperature reconstruction is likely in error over this period of time. (See Chapter 4.)

Using a nonlinear non-stationary time series technique called empirical mode decomposition, Coughlin and Tung (2004) analyzed monthly mean geopotential heights and temperatures obtained from Kalnay *et al.* (1996) from 1000 hPa to 10 hPa over the period January 1958 to December 2003. This work revealed the existence of five oscillations and a trend in both data sets. The fourth of these oscillations has an average period of 11 years and indicates enhanced warming during times of maximum solar radiation. As the two researchers describe it, "the solar flux is positively correlated with the fourth modes in temperature and geopotential height almost everywhere [and] the overwhelming picture is that of a positive correlation between the solar flux and this mode throughout the troposphere."

Coughlin and Tung concluded "the atmosphere warms during the solar maximum almost everywhere over the globe." And the unfailing omnipresent impact of this small forcing (a 0.1 percent change in the total energy output of the Sun from cycle minimum to maximum) suggests any longer-period oscillations of the solar inferno could be causing the even greater centennial- and millennial-scale oscillations of temperature observed in paleo-temperature data from around the world.

Widespread measurements have been made since the late 1950s of the flux of solar radiation received at the surface of Earth, and nearly all of these measurements reveal a sizeable decline in the surface receipt of solar radiation that was not reversed until the mid-1980s, as noted by Wild *et al.* (2005). During this time, there was also a noticeable dip in Earth's surface air temperature, after which temperatures rose at a rate and to a level of warmth the IPCC claims were without precedent over the past one to two millennia, and which they attribute to similarly unprecedented increases in greenhouse gas concentrations, mostly notably CO_2.

This reversal of the decline in the amount of solar radiation incident upon Earth's surface, in the words of Wild *et al.*, "is reconcilable with changes in cloudiness and atmospheric transmission and may substantially affect surface climate." "Whereas the decline in solar energy could have counterbalanced the increase in down-welling longwave energy from the enhanced greenhouse effect before the 1980s," they note, "the masking of the greenhouse effect and related impacts may no longer have been effective thereafter, enabling the greenhouse signals to become more evident during the 1990s." Qualitatively, this scenario sounds plausible, but when the magnitude of the increase in the surface-received flux of solar radiation over the 1990s is considered, the statement is seen to be rather disingenuous.

Over the range of years for which high-quality data were available to them (1992–2002), Wild *et al.* determined the mean worldwide increase in clear-sky insolation averaged 0.68 Wm^{-2} per year, which increase they found to be "comparable to the increase under all-sky conditions." Consequently, for that 10-year period, these data suggest the total increase in solar radiation received at the surface of Earth should have been something on the order of 6.8 Wm^{-2}, not significantly different from what is implied by the satellite and "Earthshine" data of Palle *et al.* (2004), although the satellite data of Pinker *et al.* (2005)

suggest an increase only about a third as large for this period.

Putting these numbers in perspective, Charlson *et al.* (2005) report the longwave radiative forcing provided by all greenhouse gas increases since the beginning of the industrial era has amounted to only 2.4 Wm^{-2}, citing the work of Anderson *et al.* (2003), while Palle *et al.* say "the latest IPCC report argues for a 2.4 Wm^{-2} increase in CO_2 longwave forcing since 1850." The longwave forcing of greenhouse gases over the 1990s thus would have been but a fraction of a fraction of the observed increase in the contemporary receipt of solar radiation at the surface of Earth. To suggest, as Wild *et al.* do, that the increase in insolation experienced at the surface of Earth over the 1990s may have enabled anthropogenic greenhouse gas signals of that period to become more evident seems incongruous, as their suggestion implies the bulk of the warming of that period was due to increases in greenhouse gas concentrations, when the solar component of the temperature forcing was clearly much greater. This incongruity is exacerbated by the fact that methane concentrations rose ever more slowly over this period, apparently stabilizing near the period's end (see Chapter 2). Consequently, a much more logical conclusion would be that the primary driver of the global warming of the 1990s was the large increase in global surface-level insolation.

Soon (2005) explored the question of which variable was the dominant driver of twentieth-century temperature change in the Arctic—rising atmospheric CO_2 concentrations or variations in solar irradiance—by examining what roles the two variables may have played in decadal, multidecadal, and longer-term variations in surface air temperature (SAT). He performed a number of statistical analyses on a composite Arctic-wide SAT record constructed by Polyakov *et al.* (2003), global CO_2 concentrations taken from estimates given by the NASA GISS climate modeling group, and a total solar irradiance (TSI) record developed by Hoyt and Schatten (1993, updated by Hoyt in 2005) for the period 1875–2000.

These analyses indicated a much stronger statistical relationship between SATs and TSI than between SATs and CO_2. Solar forcing generally explained more than 75 percent of the variance in decadal-smoothed seasonal and annual Arctic SATs, whereas CO_2 forcing explained only between 8 and 22 percent of the variance. Wavelet analysis further supported the case for solar forcing of the SAT record, revealing similar time-frequency characteristics for annual and seasonally averaged temperatures at decadal and multidecadal time scales. By contrast, wavelet analysis gave little or no indication of a CO_2 forcing of Arctic SSTs.

Lastovicka (2006) summarized recent advancements in the field, saying "new results from various space and ground-based experiments monitoring the radiative and particle emissions of the Sun, together with their terrestrial impact, have opened an exciting new era in both solar and atmospheric physics," stating "these studies clearly show that the variable solar radiative and particle output affects the Earth's atmosphere and climate in many fundamental ways."

Bard and Frank (2006) examined "changes on different time scales, from the last million years up to recent decades," and in doing so assessed recent claims that "the variability of the Sun has had a significant impact on global climate." The two researchers conclude the role of solar activity in causing climate change "remains unproven." But they state in the concluding sentence of their abstract, "the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: the so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500-1800)."

Beer *et al.* (2006) explored solar variability and its possible effects on Earth's climate, focusing on two types of variability in the flux of solar radiation incident on Earth. The first type, in their words, "is due to changes in the orbital parameters of the Earth's position relative to the Sun induced by the other planets," which arises from gravitational perturbations that "induce changes with characteristic time scales in the eccentricity (~100,000 years), the obliquity (angle between the equator and the orbital plane, ~40,000 years) and the precession of the Earth's axis (~20,000 years)." The second type of variability is due to variability within the Sun itself.

With respect to the latter variability, the three researchers point out direct observations of total solar irradiance above Earth's atmosphere have been made over only the past quarter-century, whereas observations of sunspots have been made and recorded for approximately four centuries. In between the time scales of these two types of measurements fall neutron count rates and aurora counts. Therefore, ^{10}Be and other cosmogenic radionuclides (such as ^{14}C)—stored in ice, sediment cores, and tree rings—

currently provide our only means of inferring solar irradiance variability on a millennial time scale. These cosmogenic nuclides "clearly reveal that the Sun varies significantly on millennial time scales and most likely plays an important role in climate change." In reference to their ^{10}Be-based derivation of a 9,000-year record of solar modulation, Beer *et al.* note its "comparison with paleoclimatic data provides strong evidence for a causal relationship between solar variability and climate change."

Nicola Scafetta, a research scientist in the Duke University physics department, and Bruce West, chief scientist in the mathematical and information science directorate of the U.S. Army Research Office in Research Triangle Park, North Carolina, developed (Scafetta and West, 2006a) "two distinct TSI reconstructions made by merging in 1980 the annual mean TSI proxy reconstruction of Lean *et al*. (1995) for the period 1900–1980 and two alternative TSI satellite composites, ACRIM (Willson and Mordvinov, 2003), and PMOD (Frohlich and Lean, 1998), for the period 1980–2000," after which they used a climate sensitivity transfer function to create twentieth century temperature histories. Their results suggested the Sun contributed some 46 to 49 percent of the 1900–2000 warming of Earth. Considering there may have been uncertainties of 20 to 30 percent in their sensitivity parameters, the two researchers suggest the Sun may have been responsible for as much as 60 percent of the twentieth century temperature rise.

Scafetta and West say the role of the Sun in twentieth century global warming has been significantly underestimated by the climate modeling community, with various energy balance models producing estimates of solar-induced warming over this period that are "two to ten times lower" than what they found. The two researchers say "the models might be inadequate because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular." They also note "theoretical models usually acknowledge as solar forcing only the direct TSI forcing," thereby ignoring "possible additional climate effects linked to solar magnetic field, UV radiation, solar flares and cosmic ray intensity modulations." It also should be noted some of these phenomena may to some degree be independent of, and thereby add to, the simple TSI forcing Scafetta and West employed, suggesting the totality of solar activity effects on climate may be even greater than what they calculated.

In a second study published that year, Scafetta and West (2006b) pointed out nearly all attribution studies begin with predetermined forcing and feedback mechanisms in the models they employ. "One difficulty with this approach," according to Scafetta and West, "is that the feedback mechanisms and alternative solar effects on climate, since they are only partially known, might be poorly or not modeled at all." Consequently, "to circumvent the lack of knowledge in climate physics," they adopt "an alternative approach that attempts to evaluate the total direct plus indirect effect of solar changes on climate by comparing patterns in the secular temperature and TSI reconstructions," where "a TSI reconstruction is not used as a radiative forcing, but as a proxy [for] the entire solar dynamics." They proceed on the assumption that "the secular climate sensitivity to solar change can be phenomenologically estimated by comparing ... solar and temperature records during the pre-industrial era, when, reasonably, only a negligible amount of anthropogenic-added climate forcing was present" and "the Sun was the only realistic force affecting climate on a secular scale."

Scafetta and West used the Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005), three alternative TSI proxy reconstructions developed by Lean *et al*. (1995), Lean (2000), and Wang *et al*. (2005), and a scale-by-scale transfer model of climate sensitivity to solar activity changes they developed (Scafetta and West, 2005, 2006a). They found a "good correspondence between global temperature and solar induced temperature curves during the pre-industrial period, such as the cooling periods occurring during the Maunder Minimum (1645–1715) and the Dalton Minimum (1795–1825)." In addition, they note since the time of the seventeenth century solar minimum, "the Sun has induced a warming of $\Delta T \sim 0.7$ K" and "this warming is of the same magnitude [as] the cooling of $\Delta T \sim 0.7$ K from the medieval maximum to the 17th century minimum." This finding, they write, "suggests the presence of a millenarian solar cycle, with ... medieval and contemporary maxima, driving the climate of the last millennium," as was first suggested fully three decades ago by Eddy (1976) in his seminal study of the Maunder Minimum.

Scafetta and West say their work provides substantive evidence for the likelihood that "solar change effects are greater than what can be explained by several climate models," citing Stevens and North (1996), the Intergovernmental Panel on Climate Change (2001), Hansen *et al*. (2002), and Foukal *et* *al*. (2004), and they note a solar change "might trigger several climate feedbacks and alter the greenhouse gas (H_2O, CO_2, CH_4, etc.) concentrations, as 420,000 years of Antarctic ice core data would also suggest (Petit *et al*., 1999)," once again reiterating "most of the Sun-climate coupling mechanisms are probably still unknown" and "might strongly amplify the effects of small solar activity increase." The researchers note in the twentieth century there was "a clear surplus warming" above and beyond what is suggested by their solar-based temperature reconstruction, such that something in addition to the Sun may have been responsible for approximately 50 percent of the total global warming since 1900.

This anomalous increase in temperature, it could be argued, was due to anthropogenic greenhouse gas emissions. However, Scafetta and West say the temperature difference since 1975, where the most noticeable part of the discrepancy occurred, may have been due to "spurious non-climatic contamination of the surface observations such as heat-island and land-use effects (Pielke *et al*., 2002; Kalnay and Cai, 2003)," which they say is also suggested by "an anomalous warming behavior of the global average land temperature vs. the marine temperature since 1975 (Brohan *et al*., 2006)."

In their next paper, Scafetta and West (2007) reconstructed a phenomenological solar signature (PSS) of climate for the Northern Hemisphere for the past four centuries that matches relatively well the instrumental temperature record since 1850 and the paleoclimate temperature proxy reconstruction of Moberg (2005). The period from 1950 to 2010 showed excellent agreement between 11- and 22-year PSS cycles when compared to smoothed average global temperature data and the global cooling that occurred since 2002.

Continuing their effort to identify a solar signal in Earth's global temperature record, in the March 2008 issue of *Physics Today* Scafetta and West (2008) began by noting the IPCC concludes "the contribution of solar variability to global warming is negligible, to a certainty of 95%," which would appear to stack the deck heavily against their being successful. Whereas "the statistical variability in Earth's average temperature is interpreted as noise" by most climate modelers and "thought to contain no useful information," Scafetta and West proposed "the variations in Earth's temperature are not noise, but contain substantial information about the source of variability," which they suggest is total solar irradiance, or TSI. The two researchers further suggest "variations in TSI are indicative of the Sun's turbulent dynamics," as represented by "changes in the number, duration, and intensity of solar flares and sunspots, and by the intermittency in the time intervals between dark spots and bright faculae," which variability has the capacity to "move the global temperature up and down for tens or even hundreds of years."

In providing support for their hypothesis, Scafetta and West point out "both the fluctuations in TSI, using the solar flare time series as a surrogate, and Earth's average temperature time series are observed to have inverse power-law statistical distributions," and the inverse power-law index "turns out to be the same for both the solar flare and temperature anomaly time series," citing the work of Scafetta and West (2003). This suggests "the statistics of the temperature anomalies inherit the statistical structure that was evident in the intermittency of the solar flare data." This finding led the two researchers to conclude "the Sun is influencing climate significantly more than the IPCC report claims" and "the current anthropogenic contribution to global warming is significantly overestimated." Citing Scafetta and West (2007), they "estimate that the Sun could account for as much as 69% of the increase in Earth's average temperature, depending on the TSI reconstruction used."

In 2009, Scafetta and Richard C. Willson, senior research scientist at Columbia's Center for Climate Systems Research, addressed whether TSI increased from 1980 to 2002 (Scafetta and Willson, 2009). The IPCC assumed there was no increase by adopting the TSI satellite composite produced by the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (see Frohlich, 2006). PMOD assumed the NIMBUS7 TSI satellite record artificially increased its sensitivity during the ACRIM-gap (1999.5–1991.75) and therefore reduced the NIMBUS7 record by 0.86 W/m^2 during the ACRIM-gap period; consequently, the TSI results changed little since 1980. This PMOD adjustment of NIMBUS7 TSI satellite data was never acknowledged by the experimental teams (Willson and Mordvinov, 2003; supporting material in Scafetta and Willson, 2009).

Scafetta and Willson proposed to resolve the ACRIM-gap calibration controversy by developing a TSI model using a proxy model based on variations of the surface distribution of solar magnetic flux designed by Krivova *et al.* (2007) to bridge the two-year gap between ACRIM1 and ACRIM2. They use this to bridge "mixed" versions of ACRIM and

PMOD TSI before and after the ACRIM-gap. Both "mixed" models show, in the authors' words, "a significant TSI increase of 0.033%/decade between the solar activity minima of 1986 and 1996, comparable to the 0.037% found in the TSI satellite ACRIM composite." They conclude "increasing TSI between 1980 and 2000 could have contributed significantly to global warming during the last three decades. Current climate models have assumed that TSI did not vary significantly during the last 30 years and have, therefore, underestimated the solar contribution and overestimated the anthropogenic contribution to global warming."

Krivova *et al.* (2007) noted "strong interest" in the subject of long-term variations of total solar irradiance or TSI "due to its potential influence on global climate," suggesting "only a reconstruction of solar irradiance for the pre-satellite period with the help of models can aid in gaining further insight into the nature of this influence." They developed a history of TSI "from the end of the Maunder minimum [about AD 1700] to the present based on variations of the surface distribution of the solar magnetic field," which was "calculated from the historical record of the sunspot number using a simple but consistent physical model," e.g., that of Solanki *et al*. (2000, 2002).

Krivova *et al*. report their model "successfully reproduces three independent data sets: total solar irradiance measurements available since 1978, total photospheric magnetic flux since 1974, and the open magnetic flux since 1868," which was "empirically reconstructed using the geomagnetic *aa*-index." Based on this model, they calculated an increase in TSI since the Maunder minimum somewhere in the range of 0.9-1.5 Wm^{-2}, which encompasses the results of several independent reconstructions derived over the past few years. In the final sentence of their paper, however, they note "all the values we obtain are significantly below the ΔTSI values deduced from stellar data and used in older TSI reconstructions," the results of which range from 2 to 16 Wm^{-2}.

Although there remains a degree of uncertainty about the true magnitude of the TSI change experienced since the end of the Maunder Minimum, the wide range of possible values suggests long-term TSI variability cannot be rejected as a plausible cause of the majority of the global warming seen since the Little Ice Age. The results of many of the studies reviewed in this section argue strongly for this scenario, while others suggest it is the only explanation that fits all the data.

Goode and Pallé (2007) state at the outset of their paper, "we know that there are terrestrial imprints of the solar cycle" even when "the implied changes in solar irradiance seem too weak to induce an imprint." They try to discern how such a small solar signal might induce such a large climatic response. They reviewed data shedding light on two important parameters of climate change—solar irradiance and terrestrial reflectance—which together determine the net sunlight absorbed by the Earth-ocean-atmosphere system, thereby setting the stage for the system's ultimate thermal response to the forcing they provide.

In attempting to "illustrate the possibilities of a Sun-albedo link," Goode and Pallé conclude "reflectance changes like the ones observed during the past two decades, if maintained over longer time periods, are sufficient to explain climate episodes like the 'Little Ice Age' without the need for significant solar irradiance variations." While they say their analysis of the problem "cannot be used to argue for a solar cycle dependence," they also note "it is … difficult to dismiss the possibility of a solar-albedo link."

Goode and Pallé conclude, "regardless of its possible solar ties," Earth's large-scale reflectance "is a much more variable climate parameter than previously thought and, thus, deserves to be studied in as much detail as changes in the Sun's output or changes in the Earth's atmospheric infrared emission produced by anthropogenic greenhouse gases." They note "long-term records of the Earth's reflectance will provide crucial input for general circulation climate models, and will significantly increase our ability to assess and predict climate change."

Shaviv (2008) attempted to quantify solar radiative forcing using oceans as a calorimeter. He evaluated three independent measures of net ocean heat flux over five decades, sea level change rate from twentieth century tide gauge records, and sea surface temperature. He found a "very clear correlation between solar activity and sea level" including the 11-year solar periodicity and phase, with a correlation coefficient of r=0.55. He also found "the total radiative forcing associated with solar cycles variations is about 5 to 7 times larger than those associated with the TSI variations, thus implying the necessary existence of an amplification mechanism, though without pointing to which one."

Shaviv argues "the sheer size of the heat flux, and the lack of any phase lag between the flux and the driving force further implies that it cannot be part of an atmospheric feedback and very unlikely to be part of a coupled atmosphere-ocean oscillation mode. It must therefore be the manifestation of real variations in the global radiative forcing." This provides "very strong support for the notion that an amplification mechanism exists. Given that the CRF [Cosmic Ray Flux]/climate links predicts the correct radiation imbalance observed in the cloud cover variations, it is a favorable candidate." These results, Shaviv says, "imply that the climate sensitivity required to explain historic temperature variations is smaller than often concluded."

Pallé *et al.* (2009) reanalyzed the overall reflectance of sunlight from Earth ("Earthshine") and recalibrated the CERES satellite data to obtain consistent results for Earth's solar reflectance. According to the authors, "Earthshine and FD [flux data] analyses show contemporaneous and climatologically significant increases in the Earth's reflectance from the outset of our Earthshine measurements beginning in late 1998 roughly until mid-2000. After that and to date, all three show a roughly constant terrestrial albedo, except for the FD data in the most recent years. Using satellite cloud data and Earth reflectance models, we also show that the decadal-scale changes in Earth's reflectance measured by Earthshine are reliable and are caused by changes in the properties of clouds rather than any spurious signal, such as changes in the Sun-Earth-Moon geometry."

Ohmura (2009) reviewed surface solar irradiance at 400 sites across the globe, finding a brightening phase from the 1920s to 1960s, followed by a 20-year dimming phase from 1960 to 1980. Then there was another 15-year brightening phase from 1990 to 2005. Ohmura finds "aerosol direct and indirect effects played about an equal weight in changing global solar radiation. The temperature sensitivity due to radiation change is estimated at 0.05 to 0.06 K/(W m^{-2})."

Long *et al.* (2009) analyzed "all-sky and clear-sky surface downwelling shortwave radiation and bulk cloud properties" from 1995 through 2007. They "show that widespread brightening has occurred over the continental United States ... averaging about 8 W m^{-2}/decade for all-sky shortwave and 5 W m^{-2}/decade for the clear-sky shortwave. This all-sky increase is substantially greater than the (global) 2 W m^{-2}/decade previously reported..." Their "results show changes in dry aerosols and/or direct aerosol effects alone cannot explain the observed changes in surface shortwave (SW) radiation, but it is likely that changes in cloudiness play a significant role."

These observations by Shaviv, Pallé, Ohmura, and Long *et al.* each point to major variations in Earth's radiative budget caused by changes in aerosols and clouds. Both are affected by natural and anthropogenic causes, including aircraft, power plants, cars, cooking, forest fires, and volcanoes. Natural forces—solar activity and cosmic rays—also modulate clouds. Later in this chapter, in Section 3.3.5, empirical evidence uncovered by Soon *et al.* (2011) for the simultaneous multidecadal modulation of the TSI and near-surface solar radiation from a unique sunshine duration record by the Japanese Meteorological Agency is discussed. When GCMs ignore or underestimate causes or modulation by solar cycles, magnetic fields, and/or cosmic rays, they overestimate the climate sensitivity of anthropogenic impacts.

Scafetta (2012) developed an "astronomical-based empirical harmonic climate model" that assumed Earth's climate system is resonating with, or synchronized to, a set of natural frequencies of the solar system (Scafetta, 2010, 2011). He indicates the major hypothesized mechanism upon which the model is based is that "the planets, in particular Jupiter and Saturn, induce solar or heliospheric oscillations that induce equivalent oscillations in the electromagnetic properties of the [Earth's] upper atmosphere," which in turn induces similar cycles in cloud cover and terrestrial albedo, "forcing the climate to oscillate in the same way." Essentially Scafetta proposes tidal effects of the large gas planets influence the solar fusion process and energy distribution across the solar system, which would ultimately also result in changes in climate on our planet Earth. Considering that lunar tidal effects cause major cyclical perturbations on Earth such as tidal ebb and flow of up to 21m, the model of planetary tides influencing the solar system does not seem unreasonable.

Scafetta tested the performance of this model "against all general circulation climate models (GCMs) adopted by the IPCC (2007) to interpret climate change during the last century." This analysis yielded a number of intriguing results. The solar scientist found "the GCMs fail to reproduce the major decadal and multi-decadal oscillations found in the global surface temperature record from 1850 to 2011," but his harmonic model (which uses cycles having periods of 9.1, 10–10.5, 20–21 and 60–62 years) "is found to well reconstruct the observed climate oscillations from 1850 to 2011." Scafetta also found his model "is able to forecast the climate oscillations from 1950 to 2011 using the data covering the period 1850–1950, and vice versa."

Scafetta concludes the results he obtained "reinforce previous claims that the relevant physical mechanisms that explain the detected climatic cycles are still missing in the current GCMs and that climate variations at the multi-decadal scales could be astronomically induced and, in first approximation, could be forecast," further noting "the presence of these large natural cycles can be used to correct the IPCC projected anthropogenic warming trend for the 21st century." In doing so, he found "the temperature may not significantly increase during the next 30 years, mostly because of the negative phase of the 60-year cycle," and IPCC-projected anthropogenic CO_2 emissions would imply a global warming of only 0.3–1.2°C by 2100, as opposed to the 1.0–3.6°C projected by the IPCC. This conclusion also would hold true if the 60-year climate cycle were a purely internal cycle ("autocycle") originating and resonating inside the climate system without major external forcing. This model is also favored by other scientists (see for example Tsonis *et al*. 2007; Douglass 2010; Wyatt *et al*. 2012). He also has tested the CMIP5 models (Scafetta 2013a,b).

Another important synthesis of the study of the Sun-climate relation was provided by Akasofu (2010), who examined a wide range of climatic records—including temperature proxies, lake and river ice break-up dates, sea ice and sea level changes, and glaciers—to document that the current warm period is largely a natural recovery from the Little Ice Age (dated by Akasofu to be between 1200–1400 and 1800–1850). Akasofu provides evidence suggesting a relatively lower solar irradiance existed during the Little Ice Age interval.

As demonstrated in the many studies referenced above, it is fairly certain the Sun was responsible for creating multi-centennial global cold and warm periods in the past, and it is quite plausible that modern fluctuations in solar output are responsible for the majority, if not entirety, of the global warming the planet experienced during the past century or so.

References

Akasofu, S.-I. 2010. On the recovery from the Little Ice Age. *Natural Science* **2**: 1211–1224.

Anderson, T.L., Charlson, R.J., Schwartz, S.E., Knutti, R., Boucher, O., Rodhe, H., and Heintzenberg, J. 2003. Climate forcing by aerosols—a hazy picture. *Science* **300**: 1103–1104.

Baliunas, S. and Jastrow, R. 1990. Evidence for long-term brightness changes of solar-type stars. *Nature* **348**: 520–522.

Bard, E. and Frank, M. 2006. Climate change and solar variability: What's new under the Sun? *Earth and Planetary Science Letters* **248**: 1–14.

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J. 1997. Solar modulation of cosmogenic nuclide production over the last millennium: comparison between ^{14}C and ^{10}Be records. *Earth and Planetary Science Letters* **150**: 453–462.

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus* **52B**: 985–992.

Beer, J., Vonmoos, M., and Muscheler, R. 2006. Solar variability over the past several millennia. *Space Science Reviews* **125**: 67–79.

Boberg, F. and Lundstedt, H. 2002. Solar wind variations related to fluctuations of the North Atlantic Oscillation. *Geophysical Research Letters* **29**: 10.1029/2002GL014903.

Bucha, V. and Bucha Jr., V. 1998. Geomagnetic forcing of changes in climate and in the atmospheric circulation. *Journal of Atmospheric and Terrestrial Physics* **60**: 145–169.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., and Jones, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research* **111**: 10.1029/2005 JD006548.

Carslaw, K.S., Harrizon, R.G., and Kirkby, J. 2002. Cosmic rays, clouds, and climate. *Science* **298**: 1732–1737.

Chambers, F.M., Ogle, M.I., and Blackford, J.J. 1999. Palaeoenvironmental evidence for solar forcing of Holocene climate: linkages to solar science. *Progress in Physical Geography* **23**: 181–204.

Charlson, R.J., Valero, F.P.J., and Seinfeld, J.H. 2005. In search of balance. *Science* **308**: 806–807.

Cliver, E.W., Boriakoff, V., and Feynman, J. 1998. Solar variability and climate change: geomagnetic and aa index and global surface temperature. *Geophysical Research Letters* **25**: 1035–1038.

Coughlin, K. and Tung, K.K. 2004. Eleven-year solar cycle signal throughout the lower atmosphere. *Journal of Geophysical Research* **109**: 10.1029/2004JD004873.

Damon, P.E. and Laut, P. 2004. Pattern of strange errors plagues solar activity and terrestrial climatic data. *EOS: Transactions, American Geophysical Union* **85**: 370, 374.

Douglass, D.H. 2010. Topology of Earth's climate indices and phase-locked states. *Physics Letters A* **374**: 4164–4168.

Douglass, D.H. and Clader, B.D. 2002. Climate sensitivity of the Earth to solar irradiance. *Geophysical Research Letters* **29**: 10.1029/2002GL015345.

Echer, M.P.S., Echer, E., Rigozo, N.R., Brum, C.G.M., Nordemann, D.J.R., and Gonzalez, W.D. 2012. On the relationship between global, hemispheric and latitudinal averaged air surface temperature (GISS time series) and solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics* **74**: 87–93.

Eddy, J.A. 1976. The Maunder Minimum. *Science* **192**: 1189–1202.

Fontenla, J.M., Harder, J., Livingston, W., Snow, M., and Woods, T. 2011. High-resolution solar spectral irradiance from extreme ultraviolet to far infrared. *Journal Geophysical Research* **116**: 10.1029/2011JD016032.

Foukal, P. 2002. A comparison of variable solar total and ultraviolet irradiance outputs in the 20th century. *Geophysical Research Letters* **29**: 10.1029/2002GL015474.

Foukal, P. 2003. Can slow variations in solar luminosity provide missing link between the Sun and climate? *EOS: Transactions, American Geophysical Union* **84**: 205, 208.

Foukal, P., North, G., and Wigley, T. 2004. A stellar view on solar variations and climate. *Science* **306**: 68–69.

Friis-Christensen, E. and Lassen, K. 1991. Length of the solar cycle: An indicator of solar activity closely associated with climate. *Science* **254**: 698–700.

Frohlich C. 2006. Solar irradiance variability since 1978: revision of the PMOD composite during solar cycle 21. *Space Science Review* **125**: 53–65. doi:10.1007/s11214-006-9046-5.

Frohlich C. 2009. Evidence of a long-term trend in total solar irradiance. *Astronomy and Astrophysics* **501**: L27–L30.

Frohlich, C. and Lean, J. 1998. The Sun's total irradiance: Cycles, trends and related climate change uncertainties since 1976. *Geophysical Research Letters* **25**: 4377–4380.

Frohlich, C. and Lean, J. 2002. Solar irradiance variability and climate. *Astronomische Nachrichten* **323**: 203–212.

Goode, P.R. and Palle, E. 2007. Shortwave forcing of the Earth's climate: Modern and historical variations in the Sun's irradiance and the Earth's reflectance. *Journal of Atmospheric and Solar-Terrestrial Physics* **69**: 1556–1568.

Hansen, J. and Lebedeff, S. 1987. Global trends of measured surface air temperature. *Journal of Geophysical Research* **92**: 13,345–13,372.

Hansen, J., Ruedy, R., Glascoe, J., and Sato, M. 1999. GISS analysis of surface temperature change. *Journal of Geophysical Research* **104**: 30,997–31,022.

Hansen, J., Sato, M., Nazarenko, L., Ruedy, R., Lacis, A., Koch, D., Tegen, I., Hall, T., Shindell, D., Santer, B., Stone, P., Novakov, T., Thomason, L., Wang, R., Wang, Y., Jacob, D., Hollandsworth, S., Bishop, L., Logan, J., Thompson, A., Stolarski, R., Lean, J., Willson, R., Levitus, S., Antonov, J., Rayner, N., Parker, D., and Christy, J. 2002. Climate forcings in Goddard Institute for Space Studies S12000 simulations. *Journal of Geophysical Research* **107**: 10.1029/2001JD001143.

Hartley, D.E., Villarin, J.T., Black, R.X., and Davis, C.A. 1998. A new perspective on the dynamical link between the stratosphere and troposphere. *Nature* **391**: 471–474.

Herman, J.R. and Goldberg, R.A. 1978. *Sun, Weather, and Climate*. NASA Special Publication SP-426360.

Hood, L., Schimanke, S., Spangehl, T., Bal, S., and Cubasch, U. 2013. The surface climate response to 11-yr solar forcing during northern winter: Observational analyses and comparisons with GCM simulations. *Journal of Climate* **in press**: doi: 10.1175/JCLI-D-12-00843.1.

Hoyt, D.V. and Schatten, K.H. 1993. A discussion of plausible solar irradiance variations, 1700-1992. *Journal of Geophysical Research* **98**: 18,895–18,906.

Hoyt, D.V. and Schatten, K.H. 1997. *The Role of the Sun in Climate Change*. Oxford University Press, New York, NY.

Huang, Y. 2013. A simulated climatology of spectrally decomposed atmospheric infrared radiation. *Journal of Climate* **26**: 1702–1715.

Idso, S.B. 1991a. The aerial fertilization effect of CO_2 and its implications for global carbon cycling and maximum greenhouse warming. *Bulletin of the American Meteorological Society* **72**: 962–965.

Idso, S.B. 1991b. Reply to comments of L.D. Danny Harvey, Bert Bolin, and P. Lehmann. *Bulletin of the American Meteorological Society* **72**: 1910–1914.

Idso, S.B. 1998. CO_2-induced global warming: a skeptic's view of potential climate change. *Climate Research* **10**: 69–82.

Ineson, S., Scaife, A.A., Knight, J.R., Manners, J.C., Dunstone, N.J., Gray, L.J., and Haigh, J.D. 2011. Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience* **4**: 753–757, doi:10.1038/NGEO1282.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: The Scientific Basis*. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Xiaosu, D., Maskell, K., and Johnson, C.A. (Eds.) Cambridge University Press, Cambridge, UK.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis*. In: Solomon, S., *et al*. (Eds.). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Jones, P.D., Parker, D.E., Osborn, T.J., and Briffa, K.R. 2001. Global and hemispheric temperature anomalies—land and marine instrumental records. In: *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Kalnay, E. and Cai, M. 2003. Impact of urbanization and land-use change on climate. *Nature* **423**: 528–531.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D. 1996. The NCEP/NCAR reanalysis 40-year project. *Bulletin of the American Meteorological Society* **77**: 437–471.

Karlén, W. 1998. Climate variations and the enhanced greenhouse effect. *Ambio* **27**: 270–274.

Kiehl, J.T., and Trenberth, K.E. 1997. Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society* **78**, 197–208.

Kodera, K. 2002. Solar cycle modulation of the North Atlantic Oscillation: Implication in the spatial structure of the NAO. *Geophysical Research Letters* **29**: 10.1029/2001GL014557.

Krivova, N.A., Balmaceda, L., and Solanki, S.K. 2007. Reconstruction of solar total irradiance since 1700 from the surface magnetic flux. *Astronomy & Astrophysics* **467**: 335–346.

Lal, D. and Peters, B. 1967. Cosmic ray produced radioactivity on the Earth. In: *Handbuch der Physik*, XLVI/2. Springer, Berlin, Germany, pp. 551–612.

Lassen, K. and Friis-Christensen, E. 2000. Reply to "Solar cycle lengths and climate: A reference revisited" by P. Laut and J. Gundermann. *Journal of Geophysical Research* **105**: 27,493–27,495.

Lastovicka, J. 2006. Influence of the Sun's radiation and particles on the Earth's atmosphere and climate—Part 2. *Advances in Space Research* **37**: 1563.

Lean, J. 2000. Evolution of the Sun's spectral irradiance since the Maunder Minimum. *Geophysical Research Letters* **27**: 2425–2428.

Lean, J., Beer, J., and Bradley, R. 1995. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Research Letters* **22**: 3195–1398.

Lean, J. and Rind, D. 1998. Climate forcing by changing solar radiation. *Journal of Climate* **11**: 3069–3094.

Lockwood, M., Stamper, R., and Wild, M.N. 1999. A doubling of the Sun's coronal magnetic field during the past 100 years. *Nature* **399**: 437–439.

Long, C. N., Dutton, E.G., Augustine, J.A., Wiscombe, W., Wild, M., McFarlane, M.A., and Flynn, C.J. 2009. Significant decadal brightening of downwelling shortwave in the continental United States. *Journal of Geophysical Research* **114:** D00D06, doi:10.1029/2008JD011263.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlén, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Nesme-Ribes, D., Ferreira, E.N., Sadourny, R., Le Treut, H., and Li, Z.X. 1993. Solar dynamics and its impact on solar irradiance and the terrestrial climate. *Journal of Geophysical Research* **98**: 18,923–18.935.

Ohmura, A. 2009. Observed decadal variations in surface solar radiation and their causes. *Journal of Geophysical Research* **114:** D00D05, doi:10.1029/2008JD011290.

Oppo, D.W., McManus, J.F., and Cullen, J.L. 1998. Abrupt climate events 500,000 to 340,000 years ago: Evidence from subpolar North Atlantic sediments. *Science* **279**: 1335–1338.

Pallé, E., Goode, P.R., Montañés-Rodríguez, P., and Koonin, S.E. 2004. Changes in Earth's reflectance over the past two decades. *Science* **304**: 1299–1301.

Pallé, E., Goode, P.R., and Montañés-Rodríguez, P. 2009. Interannual variations in Earth's reflectance 1999–2007. *Journal of Geophysical Research* **114:** D00D03, doi:10.1029/2008JD010734.

Parker, D.E., Gordon, M., Cullum, D.P.N., Sexton, D.M.H., Folland, C.K., and Rayner, N. 1997. A new global gridded radiosonde temperature data base and recent temperature trends. *Geophysical Research Letters* **24**: 1499–1502.

Parker, E.N. 1999. Sunny side of global warming. *Nature* **399**: 416–417.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.

Pielke Sr., R.A., Marland, G., Betts, R.A., Chase, T.N., Eastman, J.L., Niles, J.O., Niyogi, D.S., and Running, S.W. 2002. The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effects of greenhouse gases. *Philosophical Transactions of the Royal Society of London A* **360**: 1705–1719.

Pinker, R.T., Zhang, B., and Dutton, E.G. 2005. Do satellites detect trends in surface solar radiation? *Science* **308**: 850–854.

Pittock, A.B. 1983. Solar variability, weather and climate: An update. *Quarterly Journal of the Royal Meteorological Society* **109**: 23–55.

Polyakov, I.V., Bekryaev, R.V., Alekseev, G.V., Bhatt, U.S., Colony, R.L., Johnson, M.A., Maskshtas, A.P., and Walsh, D. 2003. Variability and trends of air temperature and pressure in the maritime Arctic, 1875-2000. *Journal of Climate* **16**: 2067–2077.

Raisbeck, G.M., Yiou, F., Jouzel, J., and Petit, J.-R. 1990. ^{10}Be and ^{2}H in polar ice cores as a probe of the solar variability's influence on climate. *Philosophical Transactions of the Royal Society of London* **A300**: 463–470.

Raymo, M.E., Ganley, K., Carter, S., Oppo, D.W., and McManus, J. 1998. Millennial-scale climate instability during the early Pleistocene epoch. *Nature* **392**: 699–702.

Reid, G.C. 1991. Solar total irradiance variations and the global sea surface temperature record. *Journal of Geophysical Research* **96**: 2835–2844.

Reid, G.C. 1997. Solar forcing and global climate change since the mid-17th century. *Climatic Change* **37**: 391–405.

Rigozo, N.R., Echer, E., Vieira, L.E.A., and Nordemann, D.J.R. 2001. Reconstruction of Wolf sunspot numbers on the basis of spectral characteristics and estimates of associated radio flux and solar wind parameters for the last millennium. *Solar Physics* **203**: 179–191.

Rozelot, J.P. 2001. Possible links between the solar radius variations and the Earth's climate evolution over the past four centuries. *Journal of Atmospheric and Solar-Terrestrial Physics* **63**: 375–386.

Scafetta, N. 2008. Comment on "Heat capacity, time constant, and sensitivity of Earth's climate system" by Schwartz. *Journal of Geophysical Research* **113**: D15104 doi:10.1029/2007JD009586.

Scafetta, N. 2010. Empirical evidence for a celestial origin of the climate oscillations and its implications. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 951–970.

Scafetta, N. 2012. A shared frequency set between the historical mid-latitude aurora records and the global surface temperature. *Journal of Atmospheric and Solar-Terrestrial Physics* **74**: 145–163.

Scafetta, N. 2012. Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation climate models. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 124–137.

Scafetta, N. 2013a. Solar and planetary oscillation control on climate change: hind-cast, forecast and a comparison with the CMIP5 GCMs. *Energy & Environment* **24**(3-4): 455–496.

Scafetta, N. 2013b. Discussion on climate oscillations: CMIP5 general circulation models versus a semi-empirical harmonic model based on astronomical cycles. *Earth Science Review* **in press**: doi: 10.1016/j.earscirev. 2013.08.008

Scafetta, N. and West, B.J. 2003. Solar flare intermittency and the Earth's temperature anomalies. *Physical Review Letters* **90**: 248701.

Scafetta, N. and West, B.J. 2005. Estimated solar contribution to the global surface warming using the ACRIM TSI satellite composite. *Geophysical Research Letters* **32**: 10.1029/2005GL023849.

Scafetta, N. and West, B.J. 2006a. Phenomenological solar contribution to the 1900-2000 global surface warming. *Geophysical Research Letters* **33**: 10.1029/2005GL025539.

Scafetta, N. and West, B.J. 2006b. Phenomenological solar signature in 400 years of reconstructed Northern Hemisphere temperature record. *Geophysical Research Letters* **33**: 10.1029/2006GL027142.

Scafetta, N. and West, B.J. 2007. Phenomenological reconstructions of the solar signature in the Northern Hemisphere surface temperature records since 1600. *Journal of Geophysical Research* **112**: D24S03, doi:10.1029/2007JD008437.

Scafetta, N. and West, B.J. 2008. Is climate sensitive to solar variability? *Physics Today* **3**: 50–51.

Scafetta, N. and Willson, R.C. 2009. ACRIM-gap and TSI trend issue resolved using a surface magnetic flux TSI proxy model. *Geophysical Research Letters* **36**: L05701, doi:10.1029/2008GL036307.

Shapiro, A.I., Schmutz, W., Rozanov, E., Schoell, M., Haberreiter, M. Shapiro, A.V., and Nyeki, S. 2011. A new approach to the long-term reconstruction of the solar irradiance leads to a large historical solar forcing. *Astronomy and Astrophysics* **529**: A67.

Shaviv, N.J. 2005. On climate response to changes in the cosmic ray flux and radiative budget. *Journal of Geophysical Research* **110**: 10.1029/2004JA010866.

Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing, *Journal of Geophysical Research* **113**: A11101, doi:10.1029/2007JA012989.

Solanki, S.K. and Fligge, M. 1998. Solar irradiance since 1874 revisited. *Geophysical Research Letters* **25**: 341–344.

Solanki, S.K., Schussler, M., and Fligge, M. 2000. Evolution of the Sun's large-scale magnetic field since the Maunder minimum. *Nature* **408**: 445–447.

Solanki, S.K., Schussler, M., and Fligge, M. 2002. Secular variation of the Sun's magnetic flux. *Astronomy & Astrophysics* **383**: 706–712.

Soon, W. W.-H. 2005. Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years. *Geophysical Research Letters* **32**:10.1029/2005GL023429.

Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 2331–2344.

Soon, W. and Legates, D.R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics* **93**: 45–56.

Soon, W., Posmentier, E., and Baliunas, S. 2000. Climate hypersensitivity to solar forcing? *Annales Geophysicae* **18**: 583–588.

Steinhilber, F., Beer, J., and Frohlich, C. 2009. Total solar irradiance during the Holocene. *Geophysical Research Letters* **36**: 10.1029/2009GL040142.

Stevens, M.J. and North, G.R. 1996. Detection of the climate response to the solar cycle. *Journal of the Atmospheric Sciences* **53**: 2594–2608.

Svensmark, H. 1998. Influence of cosmic rays on Earth's climate. *Physical Review Letters* **22**: 5027–5030.

Svensmark, H. and Friis-Christensen, E. 1997. Variation of cosmic ray flux and global cloud coverage—A missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics* **59**: 1225–1232.

Thejll, P. Christiansen, B., and Gleisner, H. 2003. On correlations between the North Atlantic Oscillation, geopotential heights, and geomagnetic activity. *Geophysical Research Letters* **30**: 10.1029/2002GL016598.

Tsonis, A.A., Swanson, K., and Kravtsov, S. 2007. A new dynamical mechanism for major climate shifts. *Geophysical Research Letters* **34**: 2007GL030288.

van Loon, H. and Labitzke, K. 2000. The influence of the 11-year solar cycle on the stratosphere below 30 km: A review. *Space Science Reviews* **94**: 259–278.

Wang, Y.-M., Lean, J.L., and Sheeley Jr., N.R. 2005. Modelling the Sun's magnetic field and irradiance since 1713. *The Astrophysical Journal* **625**:522–538.

White, W.B., Lean, J., Cayan, D.R., and Dettinger, M.D. 1997. Response of global upper ocean temperature to changing solar irradiance. *Journal of Geophysical Research* **102**: 3255–3266.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C.N., Dutton, E.G., Forgan, B., Kallis, A., Russak, V., and Tsvetkov, A. 2005. From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science* **308**: 847–850.

Willson, R.C. and Mordvinov, A.V. 2003. Secular total solar irradiance trend during solar cycles 21–23. *Geophysical Research Letters* **30**: 10.1029/2002GL 016038.

Wyatt, M.G., Kravtsov, S., and Tsonis, A.A. 2012. Atlantic Multidecadal Oscillation and Northern Hemisphere's climate variability. *Climate Dynamics* **38**: 929–949.

Zhang, Q., Soon, W.H., Baliunas, S.L., Lockwood, G.W., Skiff, B.A., and Radick, R.R. 1994. A method of determining possible brightness variations of the Sun in past centuries from observations of solar-type stars. *Astrophysics Journal* **427**: L111–L114.

3.2 Cosmic Rays

The study of extraterrestrial climatic forcing factors is primarily a study of phenomena related to the Sun. Historically, this field of inquiry began with the work of Milankovitch (1920, 1941), who linked the cyclical glaciations of the past million years to the receipt of solar radiation at the surface of Earth as modulated by variations in Earth's orbit and rotational characteristics. Subsequent investigations implicated other solar phenomena that operate on both shorter and longer timescales. This section reviews the findings of studies that involve galactic cosmic rays (GCRs).

The IPCC *Fifth Assessment Report* (AR5) does not consider cosmic rays as being capable of producing a significant forcing on Earth's climate. The Second Order Draft (SOD) of AR5, for example, opines "there is high confidence (medium evidence and high agreement*)* that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way" (p. 8.33 of the SOD of AR5, dated October 5, 2012). Furthermore, the draft claims "no robust association between changes in cosmic rays and cloudiness has been identified," while adding "in the event that such an association exists, it is very unlikely to be due to cosmic ray-induced nucleation of new aerosol particles" (p. 19 of the Technical Summary of the SOD).

By contrast, the following review of the literature clearly demonstrates the viability of GCRs as an important climate-forcing agent, where many key components of this hypothesis have been verified. The GCR theory is a growing climate forcing the IPCC must reckon with.

The field of GCR research begins with the original publication of Svensmark and Friis-Christensen (1997). A good summary can be found in the review paper of Svensmark (2007), director of the Center for Sun-Climate Research of the Danish National Space Center, who describes how he and his colleagues experimentally determined ions released to the atmosphere by galactic cosmic rays act as catalysts that significantly accelerate the formation of ultra-small clusters of sulfuric acid and water molecules that constitute the building blocks of cloud condensation nuclei. Svensmark also discusses the complex chain of expected atmospheric interactions, in particular how, during periods of greater solar activity, greater shielding of Earth occurs associated with a strong solar magnetic field. That shielding results in less cosmic rays penetrating to the lower atmosphere of the Earth, resulting in fewer cloud condensation nuclei being produced and thus fewer and less reflective low-level clouds occurring. More solar radiation is thus absorbed the surface of Earth, resulting in increasing near-surface air temperatures and global warming.

Svensmark provides support for key elements of this scenario with graphs illustrating the close correspondence between global low-cloud amount and cosmic-ray counts over the period 1984–2004. He also notes the history of changes in the flux of galactic cosmic rays estimated since 1700, which correlates well with Earth's temperature history over the same time period, starting from the latter portion of the Maunder Minimum (1645–1715), when Svensmark says "sunspots were extremely scarce and the solar magnetic field was exceptionally weak," and continuing on through the twentieth century, over which last hundred-year interval, as noted by Svensmark, "the Sun's coronal magnetic field doubled in strength."

Svensmark also cites the work of Bond *et al.* (2001), who in studying ice-rafted debris in the North Atlantic Ocean determined, in Svensmark's words, "over the past 12,000 years, there were many icy intervals like the Little Ice Age" that "alternated with warm phases, of which the most recent were the Medieval Warm Period (roughly AD 900–1300) and the Modern Warm Period (since 1900)." As Bond's 10-member team indicates, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

In expanding the timescale further, while highlighting the work of Shaviv (2002, 2003a) and Shaviv and Veizer (2003), Svensmark (2007) presents plots of reconstructed sea surface temperature anomalies and relative cosmic ray flux over the past 550 million years (Svensmark's Figure 8), during which time the solar system experienced four passages through the spiral arms of the Milky Way galaxy, with the climatic data showing "rhythmic cooling of the Earth whenever the Sun crossed the galactic midplane, where cosmic rays are locally most intense." Svensmark concludes "stellar winds and magnetism are crucial factors in the origin and viability of life on wet Earth-like planets," as are "ever-changing galactic environments and star-formation rates." Shaviv (2003b) went so far as to sketch the qualitative idea for a plausible resolution of the early faint Sun paradox by arguing for a lower cosmic ray flux from a strong solar wind (i.e., more cloud coverage to keep early Earth relatively warmer than it would be otherwise) during the very early portion of Earth's 4.5 billion-year history.

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark in his overview of the cosmic ray-climate connection. Lockwood *et al.* (1999), for example, examined measurements of the near-Earth interplanetary magnetic field in an effort to determine the total magnetic flux leaving the Sun since 1868. They showed the total magnetic flux from the Sun rose by a factor of 1.41 over the period 1964–1996, while surrogate measurements of the interplanetary magnetic field previous to this time indicate total magnetic flux had risen by a factor of 2.3 since 1901. The three researchers stated the variation in the total solar magnetic flux they found "stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field."

In commenting on the work of Lockwood *et al.*, Parker (1999) noted additional solar considerations also may have played an important part in the modern rise of global temperature. He noted the number of sunspots doubled over the prior 100 years, and one consequence of this phenomenon would have been "a much more vigorous Sun" that was slightly brighter. Parker pointed out spacecraft measurements suggest the brightness (Br) of the Sun varies by an amount $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle. During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth century Medieval Maximum), he notes, brightness variations on the order of $\Delta Br/Br \approx 0.5\%$ typically occur. He also notes the mean temperature (T) of the northern portion of the Earth varied by 1 to 2°C in association with these variations in solar activity, stating finally, "we cannot help noting that $\Delta T/T \approx \Delta Br/Br$." Furthermore, knowing sea surface temperatures are influenced by the brightness of the Sun and had risen since 1900, Parker writes, "one wonders to what extent the solar brightening [of the past century] has contributed to the increase in atmospheric temperature and CO_2" over that period. Parker reaches what he deems an "inescapable conclusion": "We will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate."

Recent findings from a Swiss team of researchers, Shapiro *et al.* (2001), indicate electromagnetic solar irradiation also probably increased much more than previously thought from the Little Ice Age until today. Based on their new study, the scientists assume an increase six times higher than the value used by the IPCC (Shapiro *et al.*, 2011; Lockwood, 2011).

Digging deeper into the cosmic ray subject, Feynman and Ruzmaikin (1999) investigated twentieth century changes in the intensity of cosmic rays incident upon Earth's magnetopause and their transmission through the magnetosphere to the upper troposphere. This work revealed "the intensity of cosmic rays incident on the magnetopause has decreased markedly during this century" and "the pattern of cosmic ray precipitation through the magnetosphere to the upper troposphere has also changed."

Solanki *et al.* (2000) developed a model of the long-term evolution of the Sun's large-scale magnetic field and compared its predictions against two proxy measures of this parameter. The model proved successful in reproducing the observed century-long doubling of the strength of the part of the Sun's magnetic field that reaches out from the Sun's surface into interplanetary space. It also indicated there is a direct connection between the length of the 11-year sunspot cycle and secular variations in solar activity that occur on timescales of centuries, such as the Maunder Minimum of the latter part of the seventeenth century, when sunspots were few and Earth was in the midst of the Little Ice Age.

One year later, using cosmic ray data recorded by ground-based neutron monitors, global precipitation data from the Climate Predictions Center Merged Analysis of Precipitation project, and estimates of monthly global moisture from the National Centers for Environmental Prediction reanalysis project, Kniveton and Todd (2001) set out to evaluate whether there is empirical evidence to support the hypothesis that solar variability (represented by changes in cosmic ray flux) is linked to climate change (manifested by changes in precipitation and precipitation efficiency) over the period 1979–1999. They determined there is "evidence of a statistically strong relationship between cosmic ray flux, precipitation and precipitation efficiency over ocean surfaces at mid to high latitudes," since variations in both precipitation and precipitation efficiency for mid to high latitudes showed a close relationship in both phase and magnitude with variations in cosmic ray flux, varying 7 to 9 percent during the solar cycle of the 1980s. Other potential forcing factors were ruled out due to poorer statistical relationships.

The same year, Bond *et al.* (2001) published the results of their study of ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). Based on analyses of deep-sea sediment cores that yielded abundance changes in time of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern, and with the help of an accelerator mass spectrometer date, a number of recurring alternate periods of relative cold and warmth that wended their way through the 12,000-year expanse of the Holocene. The mean duration of the several complete climatic cycles thus delineated was 1,340 years, and the two last cold and warm nodes of the latter oscillations, in the words of Bond *et al.*, were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period.'"

The signal accomplishment of the scientists' study was the linking of these millennial-scale climate oscillations—and their embedded centennial-scale oscillations—with similar-scale oscillations in cosmogenic nuclide production, known to be driven by contemporaneous oscillations in solar activity. Bond *et al.* reported, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum." They concluded "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the Sun are experienced throughout the world.

With respect to the near-global extent of the climatic impact of the solar radiation variations they detected, Bond *et al.* reference studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating "the footprint of the solar impact on climate we have documented extend[s] from polar to tropical latitudes." They also note "the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence." They further note their findings support previous suggestions that both the Little Ice Age and Medieval Warm Period "may have been partly or entirely linked to changes in solar irradiance."

Bond *et al.* reiterate that the oscillations in drift-ice they studied "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system." At two of their coring sites, they identified a series of such cyclical variations that extended throughout all of the previous interglacial and were "strikingly similar to those of the Holocene." Here they could also have cited the work of Oppo *et al.* (1998), who observed similar climatic oscillations in a sediment core that covered the span of time from 340,000 to 500,000 years before present, and that of Raymo *et al.* (1998), who pushed back the time of the cycles' earliest known occurrence to well over one million years ago.

How do the small changes in solar radiation inferred from the cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth's global climate? Bond *et al.* describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth's surface, provoking changes in North Atlantic deep water formation that alter the thermohaline circulation of the global ocean. They speculate "the solar signals thus may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint." Concluding their landmark paper, the researchers write the results of their study "demonstrate that the Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output," noting their work "supports the presumption that solar variability will continue to influence climate in the future."

The following year, Sharma (2002) presented the case for an even longer oscillation in solar magnetism—on the order of 100,000 years—that might bear responsibility for the recurring glacial/interglacial periods. This potential finding, which has been established for only two of the putative 100,000-year cycles and could turn out to be spurious, is based upon the fact that the production of ^{10}Be in Earth's atmosphere is affected by the intensity of magnetic activity at the surface of the Sun as well as Earth's geomagnetic dipole strength.

Using data pertaining to these factors obtained from several different sources, Sharma began his analysis by compiling 200,000-year histories of relative geomagnetic field intensity (from natural remnant magnetizations of marine sediments) and normalized atmospheric ^{10}Be production rate (also from marine sediments). Then, with the help of a theoretical construct describing the ^{10}Be production rate as a function of the solar modulation of galactic cosmic rays (arising from variations in magnetic activity at the surface of the Sun) and Earth's geomagnetic field intensity, he created a 200,000-year history of the solar modulation factor.

This history reveals the existence of significant periods of both enhanced and reduced solar activity; comparing it with the marine δ^{18}O record (a proxy for global ice volume and, therefore, Earth's mean surface air temperature), Sharma found the two histories are strongly correlated. As he describes it, "the solar activity has a 100,000-year cycle in phase with the $\delta^{18}O$ record of glacial-interglacial cycles," such that "the long-term solar activity and Earth's surface temperature appear to be directly related." Throughout the 200,000-year period, Sharma notes, "the Earth has experienced a warmer climate whenever the Sun has been magnetically more active" and "at the height of the last glacial maximum the solar activity was suppressed." It is therefore easy for Sharma to make the final connection, setting forth as a new hypothesis the proposal that "variations in solar activity control the 100,000-year glacial-interglacial cycles," just as they also appear to control other embedded and cascading climatic cycles.

In a contemporaneous study, Carslaw *et al.* (2002) began an essay on "Cosmic Rays, Clouds, and Climate" by noting the intensity of cosmic rays varies by about 15 percent over a solar cycle due to changes in the strength of the solar wind, which carries a weak magnetic field into the heliosphere that partially shields Earth from low-energy galactic charged particles. When this shielding is at a minimum, allowing more cosmic rays to impinge upon the planet, more low clouds have been observed to cover Earth, producing a tendency for lower temperatures to occur. When the opposite condition is true, a warmer Earth is to be expected because less low cloud cover is formed by this proposed mechanism.

The three researchers further note the total variation in low cloud amount over a solar cycle is about 1.7 percent, which corresponds to a change in the planet's radiation budget of about one watt per square meter (1 Wm^{-2}). This change, they say, "is highly significant when compared ... with the estimated radiative forcing of 1.4 Wm^{-2} from anthropogenic CO_2 emissions." Because of the short length of a solar cycle (11 years), the large thermal inertia of the world's oceans dampens the much greater global temperature change that would have occurred as a result of this radiative forcing had it been spread out over a much longer period of time, so the actual observed warming is a little less than 0.1°C.

Much of Carslaw *et al.*'s review focuses on mechanisms by which cosmic rays might induce the synchronous low cloud cover changes observed to accompany changes in cosmic ray intensity. The researchers begin by briefly describing the three principal mechanisms that have been suggested to function as links between solar variability and changes in Earth's weather: changes in total solar irradiance that provide variable energy input to the lower atmosphere, changes in solar ultraviolet radiation and its interaction with ozone in the stratosphere that couple dynamically to the lower atmosphere, and changes in cloud processes having significance for condensation nucleus abundances, thunderstorm electrification and thermodynamics, and ice formation in cyclones.

Focusing on the third of these mechanisms, Carslaw *et al.* note cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes. They further refine their focus to concentrate on ways by which cosmic-ray-produced ions may affect cloud droplets and ice particles. Here, they concentrate on two specific topics, what they call the ion-aerosol clear-air mechanism and the ion-aerosol near-cloud mechanism. Their review suggests what we know about these subjects is very much less than what we could know about them. Many scientists, as they describe it, believe "it is inconceivable that the lower atmosphere can be globally bombarded by ionizing radiation without producing an effect on the climate system."

Carslaw *et al.* point out cosmic ray intensity declined by about 15 percent during the past century "owing to an increase in the solar open magnetic flux by more than a factor of 2." They further report "this 100-year change in intensity is about the same magnitude as the observed change over the last solar cycle." In addition, it should be noted the cosmic ray intensity was already much lower at the start of the twentieth century than it was just after the start of the nineteenth century, when many historical records and climate proxies indicate the planet began its nearly two-century-long recovery from the Little Ice Age.

These observations strongly suggest solar-mediated variations in the intensity of cosmic rays bombarding Earth may indeed be responsible for the temperature variations of the past three centuries. They provide a much better fit to the temperature data than do atmospheric CO_2 data; and as Carslaw *et al.* remark, "if the cosmic ray-cloud effect is real, then these long-term changes of cosmic ray intensity could substantially influence climate." It is this possibility, they say, that makes it "all the more important to understand the cause of the cloudiness variations," as the cosmic ray-cloud connection may hold the key to resolving what they call this "fiercely debated geophysical phenomenon."

One year later, and noting Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), and Palle Bago and Butler (2000) had derived positive relationships between global cosmic ray intensity and low-cloud amount from infrared cloud data contained in the International Satellite Cloud Climatology Project (ISCCP) database for the years 1983–1993, Marsden and Lingenfelter (2003) used that database for the expanded period 1983–1999 to see if a similar relationship could be detected via cloud amount measurements made in the visible spectrum. This work revealed "a positive correlation at low altitudes, which is consistent with the positive correlation between global low clouds and cosmic ray rate seen in the infrared."

It is appropriate here to point out there are contemporary and active disagreements within the scientific community with respect to the empirical basis for the cosmic-ray-low cloud relation originally reported by Svensmark and Friis-Christensen (1997) and in updates by colleagues. Soon *et al.* (2000) provided such a challenge to Svensmark's empirical finding and pointed to another promising solar-weather-upper atmospheric relation involving the physico-chemical interactions of the relativistic electron precipitation events with NO_y molecules in the middle atmosphere first described in Callis *et al.* (1998). Further insights and details, as discussed in Paul Prikryl and colleagues (2009a; 2009b), involving the solar wind, aurora, and atmospheric gravity waves, also may be important in explaining physical realities and adding confidence in understanding Sun-weather-climate relations.

In 2003, Shaviv and Veizer (2003) provided additional support for a cosmic ray influence on climate, suggesting from two-thirds to three-fourths of the variance in Earth's temperature (T) over the past 500 million years may be attributable to cosmic ray flux (CRF) variations due to solar system passages through the spiral arms of the Milky Way galaxy. They presented several half-billion-year histories of T, CRF, and atmospheric CO_2 concentrations derived from various types of proxy data and found none of the CO_2 curves showed any clear correlation with the T curves, suggesting "CO_2 is not likely to be the principal climate driver." By contrast, they discovered the T trends displayed a dominant cyclic component on the order of 135 ± 9 million years and "this regular pattern implies that we may be looking at a reflection of celestial phenomena in the climate history of Earth."

That possibility is borne out by their identification of a similar CRF cycle of 143 ± 10 million years, together with the fact that the large cold intervals in the T records "appear to coincide with times of high CRF," a correspondence that would be expected from the likely chain of events: high CRF ==> more low-level clouds ==> greater planetary albedo ==> colder climate, as described by Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), Palle Bago and Butler (2000), and Marsden and Lingenfelter (2003).

What do these findings suggest about the role of atmospheric CO_2 variations with respect to global temperature change? Shaviv and Veizer begin their analysis by stating the conservative approach is to assume the entire residual variance not explained by measurement error is due to CO_2 variations. Doing so, they found a doubling of the air's CO_2 concentration could account for only about a 0.5°C increase in T. This result differs considerably, in their words, "from the predictions of the general circulation models, which typically imply a CO_2 doubling effect of ~1.5–5.5°C" but is "consistent with alternative lower estimates of 0.6-1.6°C (Lindzen, 1997)." Shaviv and Veizer's result is even more consistent with the results of the eight empirically based "natural experiments" of Idso (1998), which yield an average warming of about 0.4°C for a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration.

In another important test of a critical portion of the cosmic ray-climate connection theory, Usoskin *et al.* (2004b) compared the spatial distributions of low cloud amount (LCA) and cosmic ray-induced ionization (CRII) over the globe for the period 1984–2000. They used observed LCA data from the ISCCP-D2 database limited to infrared radiances and employed CRII values calculated by Usoskin *et al.* (2004a) at 3 km altitude, which corresponds roughly to the limiting altitude below which low clouds form. This work revealed "the LCA time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting a clear 11-year cycle in phase with CRII." In addition, they found "a one-to-one relation between the relative variations of LCA and CRII over the latitude range 20–55°S and 10–70°N" and "the amplitude of relative variations in LCA was found to increase polewards, in accordance with the amplitude of CRII variations." These findings of the five-member team of Finnish, Danish, and Russian scientists provide substantial evidence for a solar-cosmic ray linkage (the 11-year cycle of CRII) and a cosmic ray-cloud linkage (the in-phase cycles of CRII and CLA), making the full solar activity/cosmic ray/low cloud/climate change hypothesis appear to be rather robust.

In a review of the temporal variability of solar phenomena, Lean (2005) made an important but disturbing point about climate models and the Sun-climate connection: "A major enigma is that general circulation climate models predict an immutable climate in response to decadal solar variability, whereas surface temperatures, cloud cover, drought, rainfall, tropical cyclones, and forest fires show a definite correlation with solar activity (Haigh, 2001, Rind, 2002)."

Lean begins her review by noting the beginning of the Little Ice Age "coincided with anomalously low solar activity (the so-called Sporer and Maunder minima)" and "the latter part coincided with both low solar activity (the Dalton minimum) and volcanic eruptions." After discussing the complexities of this potential relationship, she considers another alternative: "Or might the Little Ice Age be simply the most recent cool episode of millennial climate-oscillation cycles?" Lean cites evidence revealing the sensitivity of drought and rainfall to solar variability, stating climate models are unable to reproduce what she called the "plethora" of Sun-climate connections. She notes simulations with climate models yield decadal and centennial variability even in the absence of external forcing, stating "arguably, this very sensitivity of the climate system to unforced oscillation and stochastic noise predisposes it to nonlinear responses to small forcings such as by the Sun."

Lean reports "various high-resolution paleo-climate records in ice cores, tree rings, lake and ocean sediment cores, and corals suggest that changes in the energy output of the Sun itself may have contributed to Sun-Earth system variability," citing the work of Verschuren *et al*. (2000), Hodell *et al*. (2001), and Bond *et al*. (2001). She notes "many geographically diverse records of past climate are coherent over time, with periods near 2,400, 208, and 90 years that are also present in the ^{14}C and ^{10}Be archives," as these isotopes (produced at the end of a complex chain of interactions initiated by galactic cosmic rays) contain information about various aspects of solar activity (Bard *et al*., 1997).

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

These results support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. Veretenenko *et al*. hypothesize GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development. Although scientists lack a complete understanding of many solar/GCR-induced climatic influences, this study highlights the growing need for such relationships to be explored. As it and others have shown, small changes in solar output can indeed induce significant changes in Earth's climate.

More recent analyses by Veretenenko and Ogurtsov (2012) and Georgieva *et al.* (2012) have added details to the intricate relationship between solar-cosmic-ray activity, plausibly mediated by geomagnetic activity, and weather-climate circulation patterns around the North Atlantic and elsewhere. Veretenenko and Ogurtsov (2012) emphasize the 60-year periodicity in some of the sun-climate relationship, while Georgieva *et al.* (2012) worked toward an explanation of the occasional time-dependence of the statistical correlations between solar and climatic variables.

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

Usoskin *et al.* (2005) note "the variation of the cosmic ray flux entering Earth's atmosphere is due to a combination of solar modulation and geomagnetic shielding, the latter adding a long-term trend to the varying solar signal." They also note "the existence of a geomagnetic signal in the climate data would support a direct effect of cosmic rays on climate." They evaluate this proposition by reproducing 1,000-year reconstructions of two notable solar-heliospheric indices derived from cosmogenic isotope data—the sunspot number and the cosmic ray flux (Usoskin *et al.*, 2003; Solanki *et al.*, 2004)—and creating a new 1,000-year air temperature history of the Northern Hemisphere by computing annual means of six different thousand-year surface air temperature series—those of Jones *et al.* (1998), Mann *et al.* (1999), Briffa (2000), Crowley (2000), Esper *et al.* (2002), and Mann and Jones (2003). In comparing these three series (solar activity, cosmic ray flux, and air temperature), Usoskin *et al.* found they "indicate higher temperatures during times of more intense solar activity (higher sunspot number, lower cosmic ray flux)." In addition, they report three different statistical tests "consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with sunspots," suggesting something in addition to solar activity must have been influencing the cosmic ray flux in order to make the flux the better correlate of temperature.

Noting Earth's geomagnetic field strength would be a natural candidate for this "something," Usoskin *et al.* compared their solar activity, cosmic ray, and temperature reconstructions with two long-term reconstructions of geomagnetic dipole moment obtained from the work of Hongre *et al.* (1998) and Yang *et al.* (2000). This effort revealed that between AD 1000 and 1700, when there was a substantial downward trend in air temperature associated with a less substantial downward trend in solar activity, there was also a general downward trend in geomagnetic field strength. Usoskin *et al.* suggested the substantial upward trend of cosmic ray flux needed to sustain the substantial rate of observed cooling (which was more than expected in light of the slow decline in solar activity) was likely due to the positive effect on the cosmic ray flux produced by the decreasing geomagnetic field strength.

After 1700, the geomagnetic field strength continued to decline, but air temperature began to rise. This "parting of company" between the two parameters, according to Usoskin *et al.*, occurred because "the strong upward trend of solar activity during that time overcompensate[d] [for] the geomagnetic effect," leading to a significant warming. In addition, some of the warming of the past century or so (15–20 percent) may have been caused by the concomitant increase in the atmosphere's CO_2 content, which would have complemented the warming produced by the solar activity and further decoupled the upward trending temperature from the declining geomagnetic field strength.

Together, these observations tend to strengthen the hypothesis that cosmic ray variability was a significant driver of changes in Earth's surface air temperature over the past millennium, and that this forcing was driven primarily by variations in solar activity modulated by the more slowly changing geomagnetic field strength of the planet, which sometimes strengthened the solar forcing and sometimes worked against it. The results leave room for only a small impact of anthropogenic CO_2 emissions on twentieth century warming.

Versteegh (2005) reviewed what was known about past climatic responses to solar forcing and their geographical coherence based upon proxy records of temperature and the cosmogenic radionuclides ^{10}Be and ^{14}C, which provide a measure of magnetized plasma emissions from the Sun that affect Earth's exposure to galactic cosmic rays. Versteegh concluded "proxy records provide ample evidence for climate change during the relatively stable and warm Holocene" and "all frequency components attributed to solar variability re-occur in proxy records of environmental change." The author emphasized "the ~90 years Gleisberg and ~200 years Suess cycles in the ^{10}Be and ^{14}C records" as well as "the ~1500 years Bond cycle which occurs in several proxy records [and] could originate from the interference between centennial-band solar cycles." Versteegh concludes "long-term climate change during the preindustrial [era] seems to have been dominated by solar forcing," and the long-term response to solar forcing "greatly exceeds unforced variability."

Harrison and Stephenson (2005) note that because the net global effect of clouds is cooling (Hartman, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF), measured daily at 0900 UT at Whiteknights, Reading (UK) from 1997–2004, with the traditional subjective determination of cloud amount made by a human observer as well as with daily average temperature. They compared the diffuse fraction measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux. They report, "across the UK, on days of high cosmic ray flux (which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by 19% ± 4%, and (ii) the diffuse fraction increases by 2% ± 0.3%." In addition, they found "during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction."

The two researchers note the last of these observations indicates diffuse radiation changes are "unambiguously due to cosmic rays." They also report, "at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR." Consequently, they suggest the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima, and "this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al*., 2003) which neglect a cosmic ray effect." In addition, although the effect they detect is small, they say it is "statistically robust" and the cosmic ray effect on clouds likely "will emerge on long time scales with less variability than the considerable variability of daily cloudiness."

Based on information that indicated a solar activity-induced increase in radiative forcing of 1.3 Wm^{-2} over the twentieth century (by way of cosmic ray flux reduction), plus the work of others (Hoyt and Schatten, 1993; Lean *et al*., 1995; Solanki and Fligge, 1998) that indicated a globally averaged solar luminosity increase of approximately 0.4 Wm^{-2} over the same period, Shaviv (2005) calculated an overall and ultimately solar activity-induced warming of 0.47°C (1.7 Wm^{-2} x 0.28°C per Wm^{-2}) over the twentieth century. Added to the 0.14°C of anthropogenic-induced warming, the calculated total warming of the twentieth century thus came to 0.61°C, noted by Shaviv to be very close to the 0.57°C temperature increase said by the IPCC to have been observed over the past century. Both Shaviv's and Idso's analyses, which mesh well with real-world data of both the recent and distant past, suggest only 15 to 20 percent (0.10°C/0.57°C) of the observed warming of the twentieth century can be attributed to the rise in the air's CO_2 content.

In another study from 2005, de Jager (2005) reviewed what was known at the time about the role of the Sun in orchestrating climate change over the current interglacial period, including changes that occurred during the twentieth century, focusing on the direct effects of solar irradiance variations and the indirect effects of magnetized plasma emissions.

With respect to solar irradiance variations, de Jager writes, "the fraction of the solar irradiance that directly reaches the Earth's troposphere is emitted by the solar photosphere [and] does not significantly vary." The variable part of this energy flux, as he continues, is emitted by chromospheric parts of centers of solar activity and "only directly influences the higher, stratospheric terrestrial layers," which "can only influence the troposphere by some form of stratosphere-troposphere coupling." With respect to magnetized plasma emissions, de Jager concludes "the outflow of magnetized plasma from the Sun and its confinement in the heliosphere influences the Earth's environment by modulating the flux of galactic cosmic radiation observed on Earth." He notes "cosmogenic radionuclides are proxies for this influence" and "the variable cosmic ray flux may influence climate via variable cloudiness."

Of these two phenomena, deJager seems to lean toward the latter as being the more significant. He notes the Northern Hemispheric temperature history developed by Moberg *et al*. (2005) "runs reasonably well parallel to" reconstructions of past solar variability derived from cosmogenic radionuclide concentrations, which are proxies for the outflow of magnetized plasma from the Sun. Perhaps most interesting in this regard is de Jager's observation that "never during the past ten or eleven millennia has the Sun been as active in ejecting magnetized plasma as during the second half of the twentieth century."

de Jager notes "a topical and much debated question is that of the cause of the strong terrestrial heating in the last few decades of the twentieth century," which "is usually ascribed to greenhouse warming." His review gives credence to the view that solar activity, especially that associated with the effects of ejected magnetized plasma on the galactic cosmic ray flux incident on Earth's atmosphere, could be responsible for the bulk of twentieth century warming as well as most of the major temperature swings (both up and down) of the Holocene.

Usoskin *et al*. (2006) say many solar scientists believe changes in solar activity have been responsible for significant changes in climate, but to demonstrate that a record of past variations in solar activity is required. They note "long-term solar activity in the past is usually estimated from cosmogenic isotopes, ^{10}Be or ^{14}C, deposited in terrestrial archives such as ice cores and tree rings," because "the production rate of cosmogenic isotopes in the atmosphere is related to the cosmic ray flux impinging on Earth," which "is modulated by the heliospheric magnetic field and is thus a proxy of solar activity." A nagging concern, however, is that the isotope records may suffer from what the five scientists call "uncertainties due to the sensitivity of the data to several terrestrial processes."

Noting the activity of a cosmogenic isotope in a meteorite represents "the time integrated cosmic ray flux over a period determined by the mean life of the radioisotope," Usoskin *et al*. reasoned "by measuring abundance of cosmogenic isotopes in meteorites which fell through the ages, one can evaluate the variability of the cosmic ray flux, since the production of cosmogenic isotopes ceases after the fall of the meteorite." If they could develop such a meteoritic-based cosmogenic isotope record, they posit, they could use it "to constrain [other] solar activity reconstructions using cosmogenic ^{44}Ti activity in meteorites which is not affected by terrestrial processes."

The researchers chose ^{44}Ti for this purpose because it has a half-life of about 59 years and is thus "relatively insensitive to variations of the cosmic ray flux on decadal or shorter time scales but is very sensitive to the level of the cosmic ray flux and its variations on a centennial scale." They compared the results of different long-term ^{10}Be- and ^{14}C-based solar activity reconstruction models with measurements of ^{44}Ti in 19 stony meteorites (chondrites) that fell between 1766 and 2001, as reported by Taricco *et al*. (2006). They determined "most recent reconstructions of solar activity, in particular those based on ^{10}Be data in polar ice (Usoskin *et al*., 2003, 2004c; McCracken *et al*., 2004) and on ^{14}C in tree rings (Solanki *et al*., 2004), are consistent with the ^{44}Ti data."

Dergachev *et al*. (2006) reviewed "direct and indirect data on variations in cosmic rays, solar activity, geomagnetic dipole moment, and climate from the present to 10–12 thousand years ago, [as] registered in different natural archives (tree rings, ice layers, etc.)." They found "galactic cosmic ray levels in the Earth's atmosphere are inversely related to the strength of the helio- and geomagnetic fields" and conclude "cosmic ray flux variations are apparently the most effective natural factor of climate changes on a large time scale." They note "changes in cloud processes under the action of cosmic rays, which are of importance for abundance of condensation nuclei and for ice formation in cyclones, can act as a connecting link between solar variability and changes in weather and climate." They cite numerous scientific studies indicating "cosmic rays are a substantial factor affecting weather and climate on time scales of hundreds to thousands of years."

Noting "there is evidence that solar activity variations can affect the cloud cover at Earth" but "it is still unclear which solar driver plays the most important role in the cloud formation," Voiculescu *et al.* (2006) used "partial correlations to distinguish between the effects of two solar drivers (cosmic rays and the UV irradiance) and the mutual relations between clouds at different altitudes." They found "a strong solar signal in the cloud cover," noting "low clouds are mostly affected by UV irradiance over oceans and dry continental areas and by cosmic rays over some mid-high latitude oceanic areas and moist lands with high aerosol concentration." They further state "high clouds respond more strongly to cosmic ray variations, especially over oceans and moist continental areas."

Gallet and Genevey (2007) documented what they call a "good temporal coincidence" between "periods of geomagnetic field intensity increases and cooling events" as measured in western Europe, where cooling events were "marked by glacier advances on land and increases in ice-rafted debris in [North Atlantic] deep-sea sediments." Their analyses revealed "a succession of three cooling periods in western Europe during the first millennium AD," the ages of which were "remarkably coincident with those of the main discontinuities in the history of Maya civilization," confirming the earlier work of Gallet *et al*. (2005), who had found a "good temporal coincidence in western Europe between cooling events recovered from successive advances of Swiss glaciers over the past 3,000 years and periods of rapid increases in geomagnetic field intensity," the latter of which were "nearly coeval with abrupt changes, or hairpin turns, in magnetic field direction."

Gallet and Genevey concluded "the most plausible mechanism linking geomagnetic field and climate remains a geomagnetic impact on cloud cover," whereby "variations in morphology of the Earth's magnetic field could have modulated the cosmic ray flux interacting with the atmosphere, modifying the nucleation rate of clouds and thus the albedo and Earth surface temperatures (Gallet *et al*., 2005; Courtillot *et al*., 2007)." These observations clearly suggest a global impact on climate, which is further suggested by the close relationship found to exist between "cooling periods in the North Atlantic and aridity episodes in the Middle East," as well as by the similar relationship demonstrated by Gallet and Genevey to have prevailed between periods of aridity over the Yucatan Peninsula and well-documented times of crisis in Mayan civilization.

In another study that took a look at the really big picture, painted by rhythmically interbedded limestone and shale or limestone and chert known as *rhythmites*, Elrick and Hinnov (2007) "(1) review the persistent and widespread occurrence of Palaeozoic rhythmites across North America, (2) demonstrate their primary depositional origin at millennial time scales, (3) summarize the range of paleo-environmental conditions that prevailed during rhythmite accumulation, and (4) briefly discuss the implications primary Palaeozoic rhythmites have on understanding the origin of pervasive late Neogene-Quaternary millennial-scale climate variability." They conclude "millennial-scale climate changes occurred over a very wide spectrum of paleoceanographic, paleogeographic, paleoclimatic, tectonic, and biologic conditions and over time periods from the Cambrian to the Quaternary." Given these observations, they note, "it is difficult to invoke models of internally driven thermohaline oceanic oscillations or continental ice sheet instabilities to explain their origin." Consequently, they suggest "millennial-scale paleoclimate variability is a more permanent feature of the Earth's ocean-atmosphere system, which points to an external driver such as solar forcing."

Kirkby (2008) reports "diverse reconstructions of past climate change have revealed clear associations with cosmic ray variations recorded in cosmogenic isotope archives, providing persuasive evidence for solar or cosmic ray forcing of the climate." He discusses two classes of microphysical mechanisms that have been proposed to connect cosmic rays with clouds, which interact significantly with fluxes of both solar and thermal radiation and, therefore, climate: "firstly, an influence of cosmic rays on the production of cloud condensation nuclei and, secondly, an influence of cosmic rays on the global electrical circuit in the atmosphere and, in turn, on ice nucleation and other cloud microphysical processes."

Kirkby observes "considerable progress on understanding ion-aerosol-cloud processes has been made in recent years, and the results are suggestive of a physically plausible link between cosmic rays, clouds and climate." "With new experiments planned or underway, such as the CLOUD facility at CERN," he states, "there are good prospects that we will have some firm answers to this question within the next few years." He points out, "the question of whether, and to what extent, the climate is influenced by solar and cosmic ray variability remains central to our understanding of the anthropogenic contribution to present climate change."

In another paper published the same year, Shaviv (2008) notes "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references. Nevertheless, it has been difficult for the IPCC to accept the logical derivative of this fact, that solar variations are driving major climate changes. The IPCC contends measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes. The dilemma might be resolved if some amplification mechanism were discovered, but most attempts to do so have been fraught with difficulty and met with much criticism. Shaviv, however, makes a good case for at least the existence of such an amplifier, and he points to a sensible candidate to fill this role.

Shaviv used "the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle" via "the study of 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 "to consistently derive the same oceanic heat flux." He demonstrated "there are large variations in the oceanic heat content together with the 11-year solar cycle" and reports the three independent data sets "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," thus "implying," as he describes it, "the necessary existence of an amplification mechanism, although without pointing to which one."

Finding it difficult to resist pointing, however, Shaviv acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis, which was suggested by Ney (1959), discussed by Dickinson (1975), and championed by Svensmark (1998). Based on "correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions," this concept, according to Shaviv, "predicts the correct radiation imbalance observed in the cloud cover variations" needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle. Shaviv concludes the solar-wind modulated CRF hypothesis is "a favorable candidate" for primary instigator of the many climatic phenomena discussed in this chapter.

Knudsen and Riisager (2009), while noting "the galactic cosmic ray (GCR) flux is also modulated by Earth's magnetic field," state "if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between Earth's magnetic field and climate." In a test of this supposition, Knudsen and Riisager set out to "compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen *et al*., 2008) with proxy records for past low-latitude precipitation (Fleitman *et al*., 2003; Wang *et al*., 2005)." The first of these proxy records is derived from a speleothem $\delta^{18}O$ record obtained from stalagmite Q5 from Qunf cave in southern Oman, and the second is derived from a similar record obtained from stalagmite DA from Dongge cave in southern China.

The two researchers say the various correlations they observed over the course of the Holocene "suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment." They note the general increase in precipitation observed over the past 1,500 years in both speleothem records "cannot be readily explained by changes in summer insolation or solar activity" but "correlates very well with the rapid decrease in dipole moment observed during this period." This relationship is explained by the fact that "a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation." Knudsen and Riisager conclude, "in addition to supporting the notion that variations in the geomagnetic field may have influenced Earth's climate in the past," their study also provides support for a link "between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system."

Concurrently, Ram *et al*. (2009) focused their attention on studies of dust in the Greenland Ice Sheet Project 2, acknowledging others have shown the dust concentration in the upper 2.8 km of the ice, spanning approximately 100,000 years, "is strongly modulated at regular periods close to 11, 22, 80 and 200 years, all of which are well-known periods of solar activity" (Ram *et al*., 1998; Ram and Stolz, 1999). But they concede "an amplifying mechanism must be at work if solar influence is to be taken seriously." They go on to describe work that largely satisfies that criterion as it applies to dust variability, indicating "changes in nucleation processes in clouds associated with the cosmic ray flux (CRF) can provide the necessary amplification," which they describe in abbreviated form as "increased solar activity —> decreased cosmic ray flux —> decreased air-Earth [downward electric] current [density (*Jz*)] —> decreased contact nucleation —> decreased precipitation —> increased dust."

Since this chain of events operates via changes in cloud characteristics, Ram *et al*. (2009) conclude it provides "circumstantial evidence for a Sun/climate connection mediated by the terrestrial CRF," which "may initiate a sufficiently large amplification mechanism that can magnify the influence of the Sun on the Earth's climate beyond the traditional radiative effects." They encourage additional work to "incorporate the effects of the CRF on *Jz* (and associated nucleation processes), and the subsequent microphysical responses, into macroscopic cloud models that can then be incorporated into global climate models." Until this is done successfully, today's climate models cannot be claimed to include all processes that may be of significance to the accurate simulation of Earth's future climate. The importance of the global electric circuit for connecting the electrically induced changes in cloud microphysics and storm vorticity, as well as plausible effects on large-scale circulation, is spelled out by Tinsley and colleagues (see Tinsley *et al.* 2007; Tinsley 2012).

Henrik Svensmark and two coauthors (Svensmark *et al.* 2009), all from the National Space Institute of the Technical University of Denmark in Copenhagen, explored the consequences of Forbush decreases (FDs) in the influx of galactic cosmic rays (GCRs) produced by periodic explosive events on the Sun that result in "magnetic plasma clouds from solar coronal mass ejections that pass near the Earth and provide a temporary shield against GCRs." Based on cloud liquid water content data obtained over the world's oceans by the Special Sounder Microwave Imager, liquid water cloud fraction data obtained by the Moderate Resolution Imaging Spectroradiometer, and data on IR detection of low clouds over the ocean by the International Satellite Cloud Climate Project, as well as FD data obtained from 130 neutron monitors world-wide and the Nagoya muon detector, Svensmark *et al*. found "substantial declines in liquid-water clouds, apparently tracking the declining cosmic rays and reaching minima some [~7] days after the GCR minima." Concurrently, they also found "parallel observations by the aerosol robotic network AERONET reveal falls in the relative abundance of fine aerosol particles, which, in normal circumstances, could have evolved into cloud condensation nuclei."

The Danish scientists say their results "show global-scale evidence of conspicuous influences of solar variability on cloudiness and aerosols." They report "the loss of ions from the air during FDs reduces the cloud liquid water content over the oceans" and note "so marked was the response to relatively small variations in the total ionization" that "a large fraction of Earth's clouds could be controlled by ionization." Such observations support Svensmark's theory that solar-activity-induced decreases in GCR bombardment of Earth lead to decreases in low (<3.2 km) clouds as a result of reduced atmospheric ionization and, therefore, less fine aerosol particles that under normal circumstances could have evolved into cloud condensation nuclei that could have resulted in more low-level clouds that could have cooled the planet.

Voiculescu and Usoskin (2012) offered some guidelines for the study of solar-GCR-cloud relation: "A consensus regarding the impact of solar variability on cloud cover is far from being reached," they note. "Our results show that solar signatures in cloud cover persist in some key climate-defining regions for the entire time period [i.e., 1984–2009] and supports the idea that, if existing, solar effects are not visible at the global level and any analysis of solar effects on cloud cover (and consequently, on climate) should be done at the regional level."

Le Mouel *et al*. (2010a) examined the Sun-climate connection on a much-reduced time scale. The team of Professors Jean-Louis Le Mouel, Vincent Courtillot, and colleagues has published several papers investigating how the Sun's variable magnetic activity may affect various terrestrial phenomena, including weather and climate (see for example Kossobokov *et al*. 2010; Le Mouel *et al*. 2010b). Their 2010 publication (Le Mouel *et al*. 2010a) adds insight to the topic.

Figure 3.2.1, for example, displays unexpected and surprising correlations between the long-term variation in the amplitude (A) of the solid Earth rotation parameter (here they have adopted its well-detected semiannual variation) called length of day, and two candidate solar activity measures: sunspot number (SN) and neutron count (NC, a proxy for incoming galactic cosmic rays), obtained from a station in Moscow, Russia. They point out A and NC are inversely correlated with SN, the solar activity index, which leads A by about one year. And since galactic cosmic rays are also inversely related to sunspot number with a delay of one to two years or so, A is directly correlated to NC.

Le Mouel *et al*. explain the correlations as being due to a plausible physical link of the 11-year solar activity cycle to a systematic modulation of tropospheric zonal wind, since winds above 30 km contribute less than 20 percent of Earth's angular momentum, as proxied by A.

They also point out that, although the IPCC and others usually rule out the role of solar irradiance impact on terrestrial climate because of the small interannual changes in the solar irradiance, such an argument does not apply to the plausible link of the large seasonal incoming solar radiation in modulating the semiannual oscillations in the length-of-day amplitude. Le Mouel *et al*. say their paper "shows that the Sun can (directly or indirectly) influence tropospheric zonal mean-winds over decadal to multidecadal time scales." And noting "zonal mean-winds constitute an important element of global atmospheric circulation," they go on to suggest, "if the solar cycle can influence zonal mean-winds, then it may affect other features of global climate as well, including oscillations such as the NAO (North Atlantic Oscillation) and MJO (Madden-Julian Oscillation), of which zonal winds are an ingredient." Thus, "the cause of this forcing," as they describe it, "likely involves some combination of solar wind, galactic cosmic rays, ionosphere-Earth currents and cloud microphysics."

Takahashi *et al. (*2010) found evidence for ~27 day variation in the Outgoing Longwave Radiation data record (a proxy of cloud amount) in

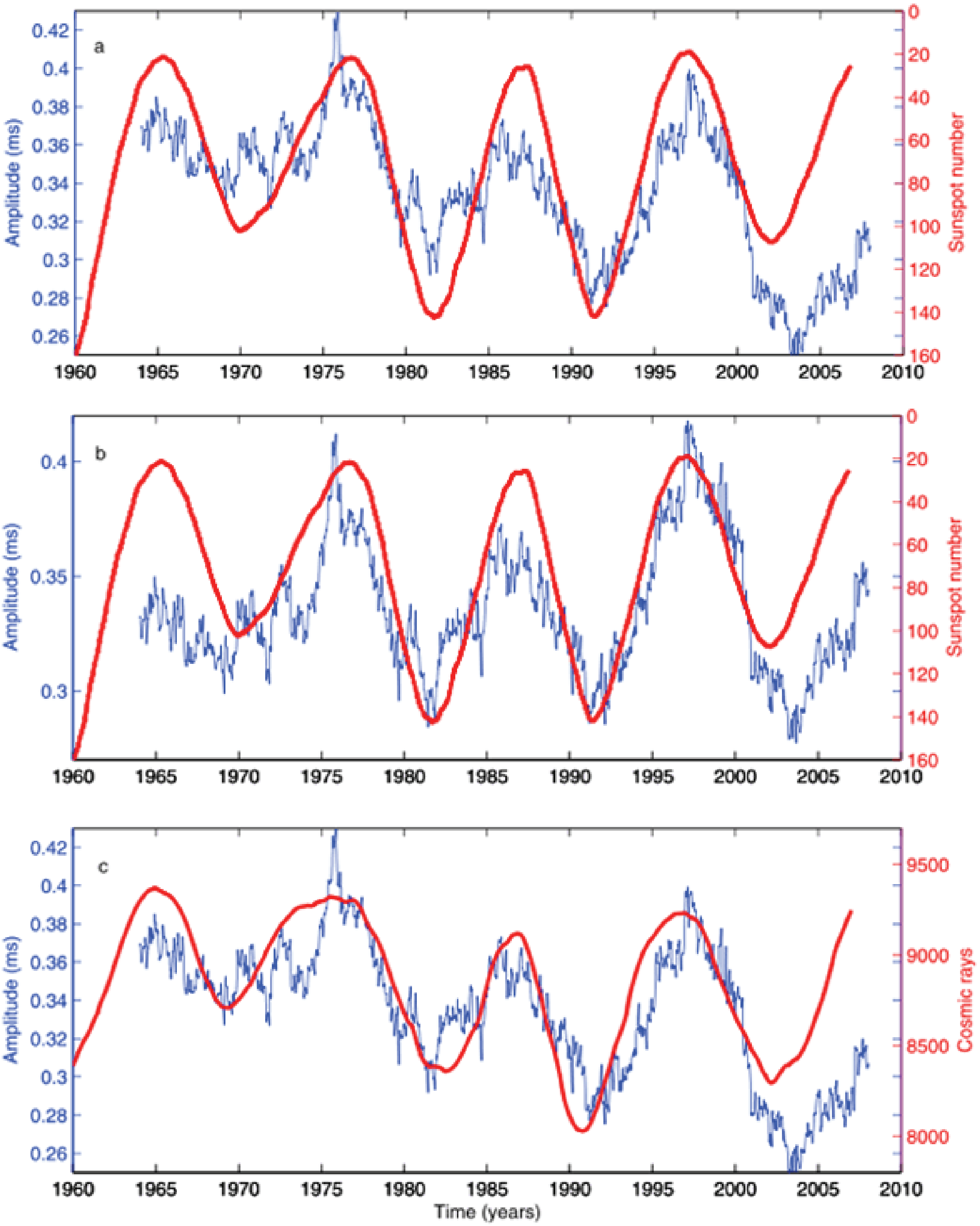

Figure 3.2.1. Correlation between the amplitude of the semiannual oscillation in length of day (blue curves with middle panel as detrended data with both top and bottom panels as original data) and various solar activity measures (sunspot numbers and proxy for galactic cosmic rays: red curves) from 1962–2009. A four-year moving-average filter was used to smooth the data series. Reprinted with permission from Le Mouel, J.-L., Kossobokov, V., and Courtillot, V. 2010b. A solar pattern in the longest temperature series from three stations in Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 62–76.

the Western Pacific warm pool region during solar activity maximum years. A significant enhancement is also found in the period of 40–60 days, corresponding to the MJO periods. A follow-up study by Hong *et al.* (2011) found further complexity in the relationship by showing the dependence of the correlations of solar rotation activity to the cloud amount on the phase of the QBO equatorial stratospheric winds. The team of Le Mouel and Courtillot follow up with the demonstration of the modulation of the MJO periods by 11-yr-like solar activity adopting both the solar UV and GCR proxies in Blanter *et al.* (2012).

Contemporaneously, Scafetta (2010) investigated less-explored solar-planetary interactions and how they might also be capable of influencing Earth's climate. Using the pattern of perturbations of the Sun's motion relative to the center of the solar system as a measure of the internal gravitational interactions of the Sun-planet system, he identified—via spectral analysis and other means—a number of clear periodic signals. A spectral decomposition of Hadley Centre climate data shows similar spectra, with the results of a spectral coherence test of the two histories being highly significant. The spectral pattern of climate model simulations does not match the solar and climatic variability patterns, whereas the output of a model based on astronomically forced cycles matches global temperature data well, and it matches ocean temperature data even better.

The mechanism behind the newly discovered suite of relationships appears to be a combination of planetary gravitational effects upon the Sun (see Scafetta 2012a,b; Scafetta and Willson, 2013a,b) that influence both direct solar irradiance and the Sun's magnetic field, plus an interaction of the magnetic fields of the other planets with Earth's magnetic field and the solar wind. Through these means the solar-terrestrial magnetic field experiences oscillations of several different frequencies, each of which exerts an influence on the intensity of cosmic rays reaching Earth and the subsequent generation of climate-changing clouds.

Two recent works by Abreu *et al.* (2012) and McCracken *et al.* (2013) reported on the interesting co-occurrences of periodic variations in the empirical solar modulation parameter (deduced from ^{14}C and ^{10}Be) and theoretical calculation of the planet-induced torque on the assumed aspherical shell of the solar tachocline. The remarkable coincidence of the five periodic changes on timescales of 88, 104, 150, 208, and 506 years should encourage further scientific investigation to find the true and correct physical mechanisms in order to explain and confirm how both the gaseous giant planets and inner terrestrial planets of our solar system together could influence the internal operation of the solar magnetic dynamo within the Sun and therefore its radiative and magnetic outputs.

One promising possibility has been proposed by Wolff and Patrone (2010), who described how the inertial motions of the Sun with respect to the barycenter of the solar system may be linked to the inner working of the solar dynamo. Wolff and Patrone also show how the orbital angular momentum of the solar inertial motion can lead to storage (and subsequent release) of potential energy within the inner solar shell through differential exchanges of mass or fluid element within the inner Sun.

The important dynamical characterization and link of the plausible planetary influences and modulations on the long-term operation of the internal solar dynamo was recently highlighted by Cionco and Campagnucci (2012). In addition, McCracken *et al.* (2013) confirm the periodic changes in millennial timescale over the past 9,400 years.

In light of the evidence presented above, the flux of galactic cosmic rays clearly wields an important influence on Earth's climate, likely much more so than that exhibited by the modern increase in atmospheric CO_2. That makes fluctuations in the Sun the primary candidate for "prime determinant" of Earth's climatic state. At the very least, these research findings invalidate the IPCC's AR5 claim that "there is high confidence (medium evidence and high agreement*)* that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way" (p. 8.33 of the SOD of AR5, dated October 5, 2012) and that "no robust association between changes in cosmic rays and cloudiness has been identified" (p. 19 of the Technical Summary of the SOD).

References

Abreu, J.A., Beer, J., Ferriz-Mas, A., McCracken, K.G., and Steinhilber, F. 2012. Is there a planetary influence on solar activity? *Astronomy and Astrophysics* **548**: A88.

Bard, E., Raisbeck, G., Yiou, F.m and Jouzel, J. 1997. Solar modulation of cosmogenic nuclide production over the last millennium: comparison between ^{14}C and ^{10}Be records. *Earth and Planetary Science Letters* **150**: 453–462.

Blanter, E., Le Mouel, J.-L., Shnirman, M., and Courtillot, V. 2012. A correlation of mean period of MJO indices and

11-yr solar variation. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 195–207.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Briffa, K.R. 2000. Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quaternary Science Review* **19**: 87–105.

Callis, L.B., Natarajan, M., Lambeth, J.D., and Baker, D.N. 1998. Solar atmospheric coupling by electrons (SOLACE) 2. Calculated stratospheric effects of precipitating electrons, 1979-1988. *Journal of Geophysical Research* **103**: 28,421–28,438.

Carslaw, K.S., Harrizon, R.G., and Kirkby, J. 2002. Cosmic rays, clouds, and climate. *Science* **298**: 1732–1737.

Cionco, R.G. and Compagnucci, R.H. 2012. Dynamical characterization of the last prolonged solar minima. *Advances in Space Research* **50**: 1434–1444.

Courtillot, V., Gallet, Y., Le Mouel, J.-L., Fluteau, F., and Genevey, A. 2007. Are there connections between the Earth's magnetic field and climate? *Earth and Planetary Science Letters* **253**: 328–339.

Crowley, T.J. 2000. Causes of climate change over the past 1000 years. *Science* **289**: 270–277.

de Jager, C. 2005. Solar forcing of climate. 1: Solar variability. *Space Science Reviews* **120**: 197–241.

Dergachev, V.A., Dmitriev, P.B., Raspopov, O.M., and Jungner, H. 2006. Cosmic ray flux variations, modulated by the solar and Earth's magnetic fields, and climate changes. 1. Time interval from the present to 10–12 ka ago (the Holocene Epoch). *Geomagnetizm i Aeronomiya* **46**: 123–134.

Dickinson, R.E. 1975. Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* **56**: 1240–1248.

Elrick M. and Hinnov, L.A. 2007. Millennial-scale paleoclimate cycles recorded in widespread Palaeozoic deeper water rhythmites of North America. *Palaeogeography, Palaeoclimatology, Palaeoecology* **243**: 348–372.

Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.

Feynman, J. and Ruzmaikin, A. 1999. Modulation of cosmic ray precipitation related to climate. *Geophysical Research Letters* **26**: 2057–2060.

Fleitmann, D., Burns, S., Mudelsee, M., Neff, U., Kramers, U., Mangini, A., and Matter, A. 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* **300**: 1737–1739.

Gallet, Y. and Genevey A. 2007. The Mayans: Climate determinism or geomagnetic determinism? *EOS: Transactions, American Geophysical Union* **88**: 129–130.

Gallet Y., Genevey, A., and Fluteau, F. 2005. Does Earth's magnetic field secular variation control centennial climate change? *Earth and Planetary Science Letters* **236**: 339–347.

Georgieva, K., Kirov, B., Koucka-Knizova, P., Mosna, Z., Kouba, D., and Asenovska, Y. 2012. Solar influences on atmospheric circulation. *Journal of Atmospheric Solar-Terrestrial Physics* **90–91**: 15–25.

Haigh, J.D. 2001. Climate variability and the influence of the Sun. *Science* **294**: 2109–2111.

Harrison, R.G. and Stephenson, D.B. 2005. Empirical evidence for a nonlinear effect of galactic cosmic rays on clouds. *Proceedings of the Royal Society A*: 10.1098/rspa.2005.1628.

Hartman, D.L. 1993. Radiative effects of clouds on Earth's climate. In: Hobbs, P.V. (Ed.) *Aerosol-Cloud-Climate Interactions*. Academic Press, New York, NY, USA.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1370.

Hong, P.K., Miyahara, H., Yokoyama, Y., Takahashi, Y., and Sato, M. 2011. Implications for low latitude cloud formations from solar activity and the quasi-biennial oscillation. *Journal of Atmospheric Solar-Terrestrial Physics* **73**: 587–591.

Hongre, L., Hulot, G., and Khokhlov, A. 1998. An analysis of the geomagnetic field over the past 2000 years. *Physics of the Earth and Planetary Interiors* **106**: 311–335.

Hoyt, D.V. and Schatten, K.H. 1993. A discussion of plausible solar irradiance variations, 1700-1992. *Journal of Geophysical Research* **98**: 18,895–18,906.

Idso, S.B. 1998. Carbon-dioxide-induced global warming: A skeptic's view of potential climate change. *Climate Research* **10**: 69–82.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001*. Cambridge University Press, New York, NY, USA.

Jones, P.D., Briffa, K.R., Barnett, T.P., and Tett, S.F.B. 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures. *The Holocene* **8**: 455–471.

Kirkby, J. 2008. Cosmic rays and climate. *Surveys in Geophysics* **28**: 333–375.

Kniveton, D.R. and Todd, M.C. 2001. On the relationship of cosmic ray flux and precipitation. *Geophysical Research Letters* **28**: 1527–1530.

Knudsen, M.F. and Riisager, P. 2009. Is there a link between earth's magnetic field and low-latitude precipitation? *Geology* **37**: 71–74.

Knudsen, M.F., Riisager, P., Donadini, F., Snowball, I., Muscheler, R., Korhonen, K., and Pesonen, L.J. 2008. Variations in the geomagnetic dipole moment during the Holocene and the past 50 kyr. *Earth and Planetary Science Letters* **272**: 319–329.

Kossobokov, V., Le Mouel, J.-L., and Courtillot, V. 2010. A statistically significant signature of multi-decadal solar activity changes in atmospheric temperatures at three European stations. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 595–606.

Le Mouel, J.-L., Blanter, E., Shnirman, M., and Courtillot, V. 2010a. Solar forcing of the semi-annual variation of length-of-day. *Geophysical Research Letters* **37**: 2010GL043185.

Le Mouel, J.-L., Kossobokov, V., and Courtillot, V. 2010b. A solar pattern in the longest temperature series from three stations in Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 62–76.

Lean, J. 2005. Living with a variable Sun. *Physics Today* **58** (6): 32–38.

Lean, J., Beer, J., and Bradley, R. 1995. Reconstruction of solar irradiance since 1610—Implications for climate change. *Geophysical Research Letters* **22**:3195–3198.

Lindzen, R.S. 1997. Can increasing carbon dioxide cause climate change? *Proceedings of the National Academy of Sciences, USA* **94**: 8335–8342.

Lockwood, M. 2011. Shining a light on solar impacts. *Nature Climate Change* **1**: 98–99.

Lockwood, M., Stamper, R., and Wild, M.N. 1999. A doubling of the Sun's coronal magnetic field during the past 100 years. *Nature* **399**: 437–439.

Macklin, M.G., Johnstone, E., and Lewin, J. 2005. Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *The Holocene* **15**: 937–943.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Marsden, D. and Lingenfelter, R.E. 2003. Solar activity and cloud opacity variations: A modulated cosmic ray ionization model. *Journal of the Atmospheric Sciences* **60**: 626–636.

Marsh, N.D. and Svensmark, H. 2000. Low cloud properties influenced by cosmic rays. *Physical Review Letters* **85**: 5004-5007.

McCracken, K.G., Beer, J., Steinhilber, F., and Abreu, J. 2013. A phenomenological study of the cosmic ray variations over the past 9400 years, and their implications regarding solar activity and the solar dynamo. *Solar Physics* **286**: 609–627.

McCracken, K.G., McDonald, F.B., Beer, J., Raisbeck, G., and Yiou, F. 2004. A phenomenological study of the long-term cosmic ray modulation, 850-1958 AD. *Journal of Geophysical Research* **109**: 10.1029/2004JA010685.

Milankovitch, M. 1920. Theorie Mathematique des Phenomenes Produits par la Radiation Solaire. Gauthier-Villars, Paris, France.

Milankovitch, M. 1941. *Canon of Insolation and the Ice-Age Problem*. Royal Serbian Academy, Belgrade, Yugoslavia.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Ney, E.P. 1959. Cosmic radiation and weather. *Nature* **183**: 451.

Palle Bago, E. and Butler, C.J. 2000. The influence of cosmic rays on terrestrial clouds and global warming. *Astronomy & Geophysics* **41**: 4.18–4.22.

Parker, E.N. 1999. Sunny side of global warming. *Nature* **399**: 416–417.

Prikryl, P., Rusin, V., and Rybansky, M. 2009a. The influence of solar wind on extratropical cyclones—Part 1: Wilcox effect revisited. *Annales Geophysicae* **27**: 1–30.

Prikryl, P., Muldrew, D.B., and Sofko, G.J. 2009b. The influence of solar wind on extratropical cyclones—Part 2: A link mediated by auroral atmospheric gravity waves? *Annales Geophysicae* **27**: 31–57.

Ram, M. and Stolz, M.R. 1999. Possible solar influences on the dust profile of the GISP2 ice core from central Greenland. *Geophysical Research Letters* **26**: 1043–1046.

Ram, M., Stolz, M.R., and Koenig, G. 1998. Eleven-year cycle of dust concentration variability observed in the dust profile of the GISP2 ice core from central Greenland: Possible solar cycle connection. *Geophysical Research Letters* **24**: 2359–2362.

Ram, M., Stolz, M.R., and Tinsley, B.A. 2009. The terrestrial cosmic ray flux: Its importance for climate. *EOS, Transactions, American Geophysical Union* **90**: 397–398.

Rind, D. 2002. The Sun's role in climate variations. *Science* **296**: 673–677.

Scafetta, N. 2010. Empirical evidence for a celestial origin of the climate oscillations and its implications. *Journal of Atmospheric Solar-Terrestrial Physics* **72**: 951–970.

Scafetta N. 2012a. Does the Sun work as a nuclear fusion amplifier of planetary tidal forcing? A proposal for a physical mechanism based on the mass-luminosity relation. *Journal of Atmospheric and Solar-Terrestrial Physics* **81-82**: 27–40.

Scafetta, N. 2012b. Multi-scale harmonic model for solar and climate cyclical variation throughout the Holocene based on Jupiter-Saturn tidal frequencies plus the 11-year solar dynamo cycle. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 296–311.

Scafetta, N. and Willson, R.C. 2013a. Planetary harmonics in the historical Hungarian aurora record (1523–1960). *Planetary and Space Science* **78:** 38–44.

Scafetta, N. and Willson, R.C. 2013b. Empirical evidences for a planetary modulation of total solar irradiance and the TSI signature of the 1.09-year Earth-Jupiter conjunction cycle. *Astrophysics and Space Science* **in press:** doi: 10.1007/s10509-013-1558-3.

Shapiro, A.I., Schmutz, W., Rozanov, E., Schoell, M., Haberreiter, M. Shapiro, A.V., and Nyeki, S. 2011. A new approach to the long-term reconstruction of the solar irradiance leads to a large historical solar forcing. *Astronomy and Astrophysics* **529**: A67.

Sharma, M. 2002. Variations in solar magnetic activity during the last 200,000 years: is there a Sun-climate connection? *Earth and Planetary Science Letters* **199**: 459–472.

Shaviv, N. 2002. Cosmic ray diffusion from the galactic spiral arms, iron meteorites, and a possible climatic connection. *Physics Review Letters* **89**: 051102.

Shaviv, N. 2003a. The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth. *New Astronomy* **8**: 39–77.

Shaviv, N.J. 2003b. Toward a solution to the early faint Sun paradox: a lower cosmic ray flux from a stronger solar wind. *Journal of Geophysical Research* **108**: 10.1029/2003JA009997.

Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* **113**: 10.1029/2007JA012989.

Shaviv, N. and Veizer, J. 2003. Celestial driver of Phanerozoic climate? *GSA Today* **13** (7): 4–10.

Solanki, S.K. and Fligge, M. 1998. Solar irradiance since 1874 revisited. *Geophysical Research Letters* **25**: 341–344.

Solanki, S.K., Schussler, M., and Fligge, M. 2000. Evolution of the Sun's large-scale magnetic field since the Maunder minimum. *Nature* **408**: 445–447.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schussler, M., and Beer, J. 2004. Unusual activity of the Sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.

Soon, W., Baliunas, S., Posmentier, E.S., and Okeke, P. 2000. Variations of solar coronal hole area and terrestrial lower tropospheric air temperature from 1979 to mid-1998: Astronomical forcings of change in Earth's climate? *New Astronomy* **4**: 563–579.

Stott, P.A., Jones, G.S., and Mitchell, J.F.B. 2003. Do models underestimate the solar contribution to recent climate change? *Journal of Climate* **16**: 4079–4093.

Svensmark, H. 1998. Influence of cosmic rays on Earth's climate. *Physical Review Letters* **81**: 5027–5030.

Svensmark, H. 2007. Cosmoclimatology: a new theory emerges. *Astronomy & Geophysics* **48**: 1.18–1.24.

Svensmark, H., Bondo, T., and Svensmark, J. 2009. Cosmic ray decreases affect atmospheric aerosols and clouds. *Geophysical Research Letters* **36**: 10.1029/2009GL038429.

Svensmark, H. and Friis-Christensen, E. 1997. Variation of cosmic ray flux and global cloud coverage—A missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics* **59**: 1225–1232.

Takahashi, Y., Okazaki, Y., Sato, M., Miyahara, H., Sakanoi, K., Hong, P.K., and Hoshino, N. 2010. 27-day variation in cloud amount in the Western Pacific warm pool region and relationship to the solar cycle. *Atmospheric Chemistry and Physics* **10**: 1577–1584.

Taricco, C., Bhandari, N., Cane, D., Colombetti, P., and Verma, N. 2006. Galactic cosmic ray flux decline and periodicities in the interplanetary space during the last 3 centuries revealed by Ti-44 in meteorites. *Journal of Geophysical Research* **111**: A08102.

Tinsley, B.A. 2012. A working hypothesis for connections between electrically-induced changes in cloud microphysics and storm vorticity, with possible effects on circulation. *Advances in Space Research* **50**: 791–805.

Tinsley, B.A. , Burns, G.B., and Zhou, L. 2007. The role of global electric circuit in solar and internal forcing of clouds and climate. *Advances in Space Research* **40**: 1126–1139.

Usoskin, I.G., Gladysheva, O.G., and Kovaltsov, G.A. 2004a. Cosmic ray-induced ionization in the atmosphere: spatial and temporal changes. *Journal of Atmospheric and Solar-Terrestrial Physics* **66**: 1791–1796.

Usoskin, I.G., Marsh, N., Kovaltsov, G.A., Mursula, K., and Gladysheva, O.G. 2004b. Latitudinal dependence of low cloud amount on cosmic ray induced ionization. *Geophysical Research Letters* **31**: 10.1029/2004GL019507.

Usoskin, I.G., Mursula, K., Solanki, S.K., Schussler, M., and Alanko, K. 2004c. Reconstruction of solar activity for the last millennium using Be-10 data. *Astronomy & Astrophysics* **413**: 745–751.

Usoskin, I.G., Schussler, M., Solanki, S.K., and Mursula, K. 2005. Solar activity, cosmic rays, and Earth's temperature: A millennium-scale comparison. *Journal of Geophysical Research* **110**: 10.1029/2004JA010946.

Usoskin, I.G., Solanki, S., Schussler, M., Mursula, K., and Alanko, K. 2003. A millennium scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s. *Physical Review Letters* **91**: 10.1103/ PhysRevLett.91.211101.

Usoskin, I.G., Solanki, S.K., Taricco, C., Bhandari, N., and Kovaltsov, G.A. 2006. Long-term solar activity reconstructions: direct test by cosmogenic ^{44}Ti in meteorites. *Astronomy & Astrophysics* **457**: 10.1051/0004-6361:20065803.

Veretenenko, S.V., Dergachev, V.A., and Dmitriyev, P.B. 2005. Long-term variations of the surface pressure in the North Atlantic and possible association with solar activity and galactic cosmic rays. *Advances in Space Research* **35**: 484–490.

Veretenenko, S.V. and Ogurtsov, M. 2012. Regional and temporal variability of solar activity and galactic cosmic ray effects on the lower atmospheric circulation. *Advances in Space Research* **49**: 770–783.

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

Versteegh, G.J.M. 2005. Solar forcing of climate. 2: Evidence from the past. *Space Science Reviews* **120**: 243–286.

Voiculescu, M. and Usoskin, I.G. 2012. Persistent solar signatures in cloud cover: Spatial and temporal analysis. *Environmental Research Letters* **7:** 10.1088/1748-9326/7/4/04404.

Voiculescu, M., Usoskin, I.G., and Mursula, K. 2006. Different response of clouds to solar input. *Geophysical Research Letters* **33:** L21802, doi:10.1029/2006GL027820.

Wang, Y.J., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, C.A., and Li, X.D. 2005. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science* **308**: 854–857.

Wolff, C.L. and Patrone, P.N. 2010. A new way that planets can affect the Sun. *Solar Physics* **266**: 227–246.

Yang, S., Odah, H., and Shaw, J. 2000. Variations in the geomagnetic dipole moment over the last 12,000 years. *Geophysical Journal International* **140**: 158–162.

3.3 Temperature

This section examines correlations between various solar indices and temperature across the globe and for various sub-regions of the planet. These findings suggest a much larger influence of the Sun on climate forcing than is acknowledged by the IPCC. For example, mutual analysis of daily total solar irradiance (TSI) and various air temperature time series reveals important statistical variability structure common to both the solar forcing and the climate system response series. Because the length of analyzed series reaches climate scale, the result can improve our understanding about climate variability.

3.3.1 Global

The claim that anthropogenic greenhouse gas emissions have been responsible for twentieth century warming is based on what Loehle (2004) calls "the standard assumption in climate research, including the IPCC reports," that "over a century time interval there is not likely to be any recognizable trend to global temperatures (Risbey *et al*., 2000), and thus the null model for climate signal detection is a flat temperature trend with some autocorrelated noise." Loehle continues, "any warming trends in excess of that expected from normal climatic variability are then assumed to be due to anthropogenic effects." That assumption misses the possibility of significant underlying climate trends or cycles.

Loehle used a pair of 3,000-year proxy climate records with minimal dating errors to characterize the pattern of climate change over the past three millennia simply as a function of time, with no attempt to make the models functions of solar activity or any other physical variable. The first of the two temperature series was the sea surface temperature (SST) record of the Sargasso Sea, derived by Keigwin

(1996) from a study of the oxygen isotope ratios of foraminifera and other organisms contained in a sediment core retrieved from a deep-ocean drilling site on the Bermuda Rise. This record provides SST data for about every 67th year from 1125 BC to 1975 AD. The second temperature series was the ground surface temperature record derived by Holmgren *et al*. (1999, 2001) from studies of stalagmites found in a cave in South Africa, with color variations caused by changes in the concentrations of humic materials entering the region's ground water that were reliably correlated with regional near-surface air temperature.

Loehle used these two specific records because "most other long-term records have large dating errors, are based on tree rings, which are not reliable for this purpose (Broecker, 2001), or are too short for estimating long-term cyclic components of climate." Also, in a repudiation of the approach employed by Mann *et al*. (1998, 1999) and Mann and Jones (2003), he reports "synthetic series consisting of hemispheric or global mean temperatures are not suitable for such an analysis because of the inconsistent timescales in the various data sets," noting further, as a result of his own testing, "when dating errors are present in a series, and several series are combined, the result is a smearing of the signal."

Can only two temperature series reveal the pattern of global temperature change? According to Loehle, "a comparison of the Sargasso and South Africa series shows some remarkable similarities of pattern, especially considering the distance separating the two locations," suggesting "the climate signal reflects some global pattern rather than being a regional signal only." He also notes a comparison of the mean record with the South Africa and Sargasso series from which it was derived "shows excellent agreement" and "the patterns match closely." He notes "this would not be the case if the two series were independent or random."

Loehle fits seven time-series models to the two temperature series and to the average of the two series, using no data from the twentieth century. In all seven cases, good to excellent fits were obtained. As one example, the three-cycle model he fit to the averaged temperature series had a simple correlation of 0.58 and an 83 percent correspondence of peaks when evaluated by a moving window count.

Comparing the forward projections of the seven models through the twentieth century, Loehle notes six of the models "show a warming trend over the 20th century similar in timing and magnitude to the Northern Hemisphere instrumental series," and "one of the models passes right through the 20th century data." Such results suggest "20th century warming trends are plausibly a continuation of past climate patterns" and, therefore, that "anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes."

Loehle's analyses also reveal a long-term linear cooling trend of 0.25°C per thousand years since the peak of the interglacial warm period that occurred some 7,000 years ago, essentially identical to the mean value of the trend derived from seven prior assessments of its magnitude and five prior climate reconstructions. In addition, Loehle's analyses reveal the existence of the Medieval Warm Period of 800–1200 AD, which was shown to have been significantly warmer than the Current Warm Period experienced to date, as well as the existence of the Little Ice Age of 1500–1850 AD, shown to have been the coldest period of the entire 3,000-year record.

Loehle cites 16 peer-reviewed scientific journal articles documenting the existence of the Medieval Warm Period in all parts of the world and 18 other articles documenting the worldwide occurrence of the Little Ice Age. In one of the more intriguing aspects of his study—of which Loehle makes no mention—both the Sargasso Sea and South African temperature records reveal the existence of a major temperature spike beginning in the early 1400s. This abrupt warming pushed temperatures considerably above the peak warmth of the twentieth century before falling back to pre-spike levels in the mid-1500s. Loehle's work thus provides support for the similar finding of higher-than-current temperatures at that time by McIntyre and McKitrick (2003) in their reanalysis of the data employed by Mann *et al.* to create their controversial "hockey stick" temperature history, which gives no indication of the occurrence of this high-temperature regime.

The models developed by Loehle also reveal the existence of three climate cycles previously identified by others. Loehle's seventh model, for example, identifies a 2,388-year cycle he describes as comparing "quite favorably to a cycle variously estimated as 2200, 2300, and 2500 years (Denton and Karlén, 1973; Karlén and Kuylenstierna, 1996; Magny, 1993; Mayewski *et al*., 1997)." There is also a 490-year cycle that likely "corresponds to a 500-year cycle found previously (e.g. Li *et al*., 1997; Magny, 1993; Mayewski *et al*., 1997)" and a 228-year cycle that "approximates the 210-year cycle found by Damon and Jirikowic (1992)."

The compatibility of these findings with those of other studies that have identified solar forcing signals caused Loehle to conclude, "solar forcing (and/or other natural cycles) is plausibly responsible for some portion of 20th century warming."

Other data sets also have provided evidence of a solar influence on temperature. Van Geel *et al.* (1999), for example, reviewed what was known at the time about the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. This analysis indicated "there is mounting evidence suggesting that the variation in solar activity is a cause for millennial scale climate change," which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth's orbit about the Sun. They also reviewed the evidence for mechanisms by which the solar-climate connection might be implemented, concluding "the climate system is far more sensitive to small variations in solar activity than generally believed" and "it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation."

For the period 1856 to 2002, Scafetta and West (2003) compared the form of statistical fluctuations in the intermittency of solar flare activity with the form of statistical fluctuations in Earth's near-surface air temperature as expressed as anomalies relative to the 1961–1990 mean. Both parameters studied were shown to possess time series properties characteristic of dynamical stochastic processes bearing imprints of a particular form of variability called a Levy-walk. The authors report "the affinity of the scaling exponents obtained through our analysis suggests that the Earth's temperature anomalies inherit a Levy-walk memory component from the intermittency of solar flares," which in turn suggests Earth's near-surface air temperature fluctuations arise from variations in solar flare activity.

Scafetta and West found the best correspondence to solar flare variability was obtained for ocean, as opposed to land, temperatures. The oceans, due to their much greater compositional homogeneity and higher heat capacity, would be expected to mirror solar activity better than land masses do. It is also important to note the authors' analysis dealt with short timescales, ranging from weeks to months. Over timescales of tens to hundreds of years, they note, correlations between solar activity and temperature have been well established. The shorter timescale correlation they discovered implies a stronger physical connection between Earth's climate and solar activity than most scientists had previously thought likely. This finding, in the words of Schewe *et al.* (2003), "suggests that for the large part, variations in global temperatures are beyond our control and are instead at the mercy of the Sun's activity."

The 16 authors of Mayewski *et al.* (2004) examined 50 globally distributed paleoclimate records in search of evidence for what they call rapid climate change (RCC) over the Holocene. This terminology is not to be confused with the rapid climate changes typical of glacial periods but is used in place of what the authors call the "more geographically or temporally restrictive terminology such as 'Little Ice Age' and 'Medieval Warm Period.'" RCC events, as they also call them, are multi-century periods of time characterized by extremes of thermal and/or hydrological properties, rather than the much shorter periods of time during which the changes that led to these situations took place.

Mayewski *et al.* identify six RCCs during the Holocene: 9,000–8,000, 6,000–5,000, 4,200–3,800, 3,500–2,500, 1,200–1,000, and 600–150 cal yr BP, the last two of which intervals are the "globally distributed" Medieval Warm Period and Little Ice Age, respectively. With respect to these two periods, they write "the short-lived 1200–1000 cal yr BP RCC event coincided with the drought-related collapse of Maya civilization and was accompanied by a loss of several million lives (Hodell *et al.*, 2001; Gill, 2000), while the collapse of Greenland's Norse colonies at ~600 cal yr BP (Buckland *et al.*, 1995) coincides with a period of polar cooling."

The international team of scientists writes, "of all the potential climate forcing mechanisms, solar variability superimposed on long-term changes in insolation (Bond *et al.*, 2001; Denton and Karlén, 1973; Mayewski *et al.*, 1997; O'Brien *et al.*, 1995) seems to be the most likely important forcing mechanism." They also note "negligible forcing roles are played by CH_4 and CO_2" and "changes in the concentrations of CO_2 and CH_4 appear to have been more the result than the cause of the RCCs."

Raspopov *et al.* (2008), a team of eight researchers from China, Finland, Russia, and Switzerland, describe evidence making the case for a causative link, or set of links, between solar forcing and climate change.

Working with tree-ring width data obtained from two types of juniper found in Central Asia—

Juniperus turkestanica (related to variations in summer temperature in the Tien Shan Mountains) and *Sabina przewalskii* (related to variations in precipitation on the Qinghai-Tibetan Plateau)—Raspopov *et al*. employed band-pass filtering in the 180- to 230-year period range, wavelet transformation (Morlet basis) for the range of periods between 100 and 300 years, and spectral analysis in order to compare the variability in the two tree-ring records with independent $\Delta^{14}C$ variations representative of the approximate 210-year de Vries solar cycle over the past millennium. They found the approximate 200-year cyclical variations present in the palaeoclimatic reconstructions were well correlated ($R^2 = 0.58\text{-}0.94$) with similar variations in the $\Delta^{14}C$ data, suggesting the existence of a solar-climate connection. In addition, they say "the de Vries cycle has been found to occur not only during the last millennia but also in earlier epochs, up to hundreds of millions [of] years ago."

After reviewing additional sets of published palaeoclimatic data from various parts of the world, the eight researchers concluded the same periodicity is evident in Europe, North and South America, Asia, Tasmania, Antarctica, and the Arctic, as well as "sediments in the seas and oceans," citing 20 independent research papers in support of this statement. They conclude there is "a pronounced influence of solar activity on global climatic processes" related to "temperature, precipitation and atmospheric and oceanic circulation."

Raspopov *et al*. also report there can sometimes be "an appreciable delay in the climate response to the solar signal," as long as 150 years, and they note regional climate responses to the de Vries cycle "can markedly differ in phase," even at distances of only hundreds of kilometers, because of "the nonlinear character of the atmosphere-ocean system response to solar forcing." Nevertheless, their work testifies to the validity of their primary conclusion, that throughout the past millennium and stretching back in time as much as 250 million years, the de Vries cycle has been "one of the most intense solar activity periodicities that affected climatic processes." As for the more recent historical significance of the de Vries cycle, Raspopov *et al*. write "the temporal synchrony between the Maunder, Sporer, and Wolf minima and the expansion of Alpine glaciers (Haeberlie and Holzhauser, 2003) further points to a climate response to the deep solar minima."

Wanner *et al*. (2008)—18 climate scientists from 13 research institutions in Switzerland, Germany, the United Kingdom, Belgium, and Russia—developed "a general framework for understanding climate changes during the last 6000 years." They analyzed several hundred papers and concluded, among other things, "at decadal to multi-century timescales, climate variability shows a complex picture with indications of a possible role for (i) rapid changes of the natural forcing factors such as solar activity fluctuations and/or large tropical volcanic eruptions, (ii) internal variability including ENSO [El Niño Southern Oscillation] and NAO [North Atlantic Oscillation], (iii) changes of the thermohaline circulation, and (iv) complex feedback mechanisms between ocean, atmosphere, sea ice and vegetation."

Wanner *et al*. also report "notable swings occurred between warm and cold periods, especially the hemispheric-scale warming leading into the Medieval Warm Period and subsequent cooling into the Little Ice Age," the latter of which periods they say "appears at least to be a hemispheric phenomenon." They also note model simulations support the inference that the Little Ice Age "may have been brought about by the coincidence of low Northern Hemisphere orbital forcing during the Late Holocene with unusually low solar activity and a high number of major volcanic events."

de Jager and Duhau (2009) note "solar activity is regulated by the solar dynamo," "the dynamo is a non-linear interplay between the equatorial and polar magnetic field components," and "so far, in Sun-climate studies, only the equatorial component has been considered as a possible driver of tropospheric temperature variations." Thus they set out to examine the neglected polar field's possible influence on global temperature.

Based on "direct observations of proxy data for the two main solar magnetic field components since 1844," de Jager and Duhau derived "an empirical relation between tropospheric temperature variation and those of the solar equatorial and polar activities." When the two researchers applied this relationship to the period 1610–1995, they found a rising linear association for temperature vs. time, upon which were superimposed "some quasi-regular episodes of residual temperature increases and decreases, with semi-amplitudes up to ~0.3°C," and they note "the present period of global warming is one of them."

de Jager and Duhau conclude, "the amplitude of the present period of global warming does not significantly differ from the other episodes of relative warming that occurred in earlier centuries." The late twentieth century episode of relative warming is merely "superimposed on a relatively higher level of solar activity than the others," giving it the appearance of being unique when it isn't.

Mazzarella (2008) analyzed historical series of solar wind turbulence, atmospheric circulation, the rotation of Earth (length of day, LOD), and sea surface temperature, finding an impressive correlation of R=-0.97 between the aa index and zonal pressure (ZI), when aa was shifted ahead five years. Between ZI and LOD the correlation was R=-0.87 with a lag of six years, while the correlation between LOD and SST was R=-0.97 with a lag of four years. Such relationships suggest an increase in solar wind speed causes a decrease in zonal atmospheric circulation after five years, which causes a deceleration of Earth's rotation after four years, which ultimately causes a decrease in sea surface temperature after four years. A 60-year cycle in LOD was identified previously by Mazzarella (2007) at a confidence level greater than 99 percent. If the observed past correlation between LOD and SST continues in the future, the identified 60-year cycle hints toward a possible decline in SST starting in 2005. Recent data seem to support such a result.

Qian and Lu (2010) point out, "to understand the causes of 20th century global warming, the contributions of natural variability and human activities need to be determined," adding "to make sound predictions for this century's climate, understanding past climate change is important." They began with the reconstructed global-mean temperature anomaly history of Mann *et al*. (2008), combined with HadCRUT3 data for 1000–2008, relative to 1961–1990 (Brohan *et al*., 2006). After removing the mean temperatures of the Medieval Warm Period (MWP), Little Ice Age (LIA), and what they denoted the Global Warming Period (GWP), they used a wavelet transform procedure to identify four oscillations in the millennial temperature time series with periods of 21.1, 62.5, 116.0, and 194.6 years.

Next, they examined a reconstructed 400-year solar radiation series based on ^{10}Be data (Lean *et al*., 1995; Bard and Frank, 2006), using the results they obtained "to analyze their causality relationship" with the periodic oscillations they had detected in the reconstructed millennial global-mean temperature series. The two Chinese researchers thus determined "the ~21-year, ~115-year and ~200-year periodic oscillations in global-mean temperature are forced by and lag behind solar radiation variability," and the "relative warm spells in the 1940s and the beginning of the 21st century resulted from overlapping of warm phases in the ~21-year and other oscillations." They note "between 1994 and 2002 all four periodic oscillations reached their peaks and resulted in a uniquely warm decadal period during the last 1000 years," representing the approximate temporal differential between the current Global Warming Period and the prior Medieval Warm Period.

It is important to note Qian and Lu did not need greenhouse gas emissions data to reconstruct the past thousand-year history of Earth's global mean temperature; it was sufficient merely to employ known oscillations in solar radiation variability. The two authors write, "global-mean temperature will decline to a renewed cooling period in the 2030s, and then rise to a new high-temperature period in the 2060s." Given the cessation in warming observed in the surface and lower tropospheric temperature records over the past decade, it appears their prediction is well on its way to being validated.

It is becoming increasingly clear that the millennial-scale oscillation of climate throughout the Holocene is the result of similar-scale oscillations in some aspect of solar activity. As Mayewski *et al.* (2004) suggested a decade ago, "significantly more research into the potential role of solar variability is warranted, involving new assessments of potential transmission mechanisms to induce climate change and potential enhancement of natural feedbacks that may amplify the relatively weak forcing related to fluctuations in solar output."

References

Bard, E. and Frank, M. 2006. Climate change and solar variability: What's new under the sun? *Earth and Planetary Science Letters* **248**: 1–14.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Broecker, W.S. 2001. Was the Medieval Warm Period global? *Science* **291**: 1497–1499.

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., and Jones, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *Journal of Geophysical Research* **111**: 10.1029/2005JD006548.

Buckland, P.C., Amorosi, T., Barlow, L.K., Dugmore, A.J., Mayewski, P.A., McGovern, T.H., Ogilvie, A.E.J., Sadler, J.P., and Skidmore, P. 1995. Bioarchaeological evidence and climatological evidence for the fate of Norse farmers in medieval Greenland. *Antiquity* **70**: 88–96.

Damon, P.E. and Jirikowic, J.L. 1992. Solar forcing of global climate change? In: Taylor, R.E., Long, A. and Kra, R.S. (Eds.) *Radiocarbon After Four Decades*. Springer-Verlag, Berlin, Germany, pp. 117–129.

de Jager, C. and Duhau, S. 2009. Episodes of relative global warming. *Journal of Atmospheric and Solar-Terrestrial Physics* **71**: 194–198.

Denton, G.H. and Karlén, W. 1973. Holocene climate variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.

Gill, R.B. 2000. *The Great Maya Droughts: Water, Life, and Death*. University of New Mexico Press, Albuquerque, New Mexico, USA.

Haeberli, W. and Holzhauser, H. 2003. Alpine glacier mass changes during the past two millennia. *PAGES News* **1** (1): 13–15.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1369.

Holmgren, K., Karlén, W., Lauritzen, S.E., Lee-Thorp, J.A., Partridge, T.C., Piketh, S., Repinski, P., Stevenson, C., Svanered, O., and Tyson, P.D. 1999. A 3000-year high-resolution stalagmite-based record of paleoclimate for northeastern South Africa. *The Holocene* **9**: 295–309.

Holmgren, K., Tyson, P.D., Moberg, A., and Svanered, O. 2001. A preliminary 3000-year regional temperature reconstruction for South Africa. *South African Journal of Science* **99**: 49–51.

Idso, S.B. 1988. Greenhouse warming or Little Ice Age demise: A critical problem for climatology. *Theoretical and Applied Climatology* **39**: 54–56.

Karlén, W. and Kuylenstierna, J. 1996. On solar forcing of Holocene climate: evidence from Scandinavia. *The Holocene* **6**: 359–365.

Kärner, O. 2009. ARIMA representation for daily solar irradiance and surface air temperature time series. *Journal of Atmospheric and Solar-Terrestrial Physics* **71**: 841–847.

Kärner, O, and C. de Freitas 2011. Modelling long-term variability in daily air temperature time series for Southern Hemisphere stations. *Environmental Modelling and Assessment* 17: 221–229.

Kärner, O. and C.R. de Freitas 2013. Detecting climate variability signals in long air temperature records. *International Journal of Climatology* **in press**: doi: 10.1002/joc.3797.

Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.

Lean, J., Beer, J., and Bradley, R. 1995. Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophysical Research Letters* **22**: 3195–3198.

Li, H., Ku, T.-L., Wenji, C., and Tungsheng, L. 1997. Isotope studies of Shihua Cave; Part 3, Reconstruction of paleoclimate and paleoenvironment of Beijing during the last 3000 years from delta and ^{13}C records in stalagmite. *Dizhen Dizhi* **19**: 77–86.

Loehle, C. 2004. Climate change: detection and attribution of trends from long-term geologic data. *Ecological Modelling* **171**: 433–450.

Magny, M. 1993. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* **40**: 1–9.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Mann, M.E., Zhang, Z.H., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., and Ni, F. 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences USA* **105**: 13,252–13,257.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., and Prentice, M. 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research* **102**: 26,345–26,366.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

Mazzarella A. The 60-year modulation of global air temperature: the Earth's rotation and atmospheric circulation connection. 2007. *Theoretical and Applied Climatology* **88**: 193–99.

Mazzarella A. Solar forcing of changes in atmospheric circulation, Earth's rotation and climate. 2008. *The Open Atmospheric Science Journal* **2**: 181–184.

McIntyre, S. and McKitrick, R. 2003. Corrections to the Mann *et al.* (1998) proxy data base and Northern Hemispheric average temperature series. *Energy and Environment* **14**: 751–771.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.E. 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* **270**: 1962–1964.

Qian, W.-H. and Lu, B. 2010. Periodic oscillations in millennial global-mean temperature and their causes. *Chinese Science Bulletin* **55**: 4052–4057.

Raspopov, O.M., Dergachev, V.A., Esper, J., Kozyreva, O.V., Frank, D., Ogurtsov, M., Kolstrom, T., and Shao, X. 2008. The influence of the de Vries (~200-year) solar cycle on climate variations: Results from the Central Asian Mountains and their global link. *Palaeogeography, Palaeoclimatology, Palaeoecology* **259**: 6–16.

Risbey, J.S., Kandlikar, M., and Karoly, D.J. 2000. A protocol to articulate and quantify uncertainties in climate change detection and attribution. *Climate Research* **16**: 61–78.

Scafetta, N. 2009. Empirical analysis of the solar contribution to global mean air surface temperature change. *Journal of Atmospheric and Solar-Terrestrial Physics* **71**: 1916–1923.

Scafetta, N. and West, B.J. 2003. Solar flare intermittency in the Earth temperature anomalies. *Physical Review Letters* **90**: 248701.

Schewe, P.F., Stein, B., and Riordon, J. 2003. *The American Institute of Physics Bulletin of Physics News*. No. 642. 18 June 2003.

Van Geel, B., Raspopov, O.M., Renssen, H., van der Plicht, J., Dergachev, V.A., and Meijer, H.A.J. 1999. The role of solar forcing upon climate change. *Quaternary Science Reviews* **18**: 331–338.

Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* **27**: 1791–1828.

3.3.2 Northern Hemisphere

Evidence of the influence of the Sun on Northern Hemisphere temperatures can be found in the research of Bond *et al.* (2001), who examined ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides (^{10}Be and ^{14}C) sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). This study is described in depth in Section 3.2 of this chapter.

Bond *et al.* found "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum" and "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the solar inferno are experienced throughout the world. Bond *et al.* also observed the oscillations in drift-ice they studied "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system."

Björck *et al.* (2001) assembled a wide range of lacustrine, tree-ring, ice-core, and marine records that reveal a Northern Hemispheric and possibly global cooling event of less than 200 years' duration with a 50-year cooling-peak centered at approximately 10,300 years BP. According to the authors, the onset of the cooling event broadly coincided with rising ^{10}Be fluxes, indicative of decreased solar or geomagnetic forcing; and because "no large magnetic field variation that could have caused this event has been found," the authors postulate "the ^{10}Be maximum was caused by distinctly reduced solar forcing." They also note the onset of the Younger Dryas is coeval with a rise in ^{10}Be flux, as is the Preboreal climatic oscillation.

Pang and Yau (2002) assembled and analyzed a vast amount of data pertaining to phenomena that have been linked reliably to variations in solar activity, including frequencies of sunspot and aurora sightings, the abundance of carbon-14 in the rings of long-lived trees, and the amount of beryllium-10 in the annual ice layers of polar ice cores. For their analysis of sunspot sightings, the authors used a catalogue of 235 Chinese, Korean, and Japanese records compiled by Yau (1988), a catalogue of 270 Chinese records compiled by Zhuang and Wang (1988), a time chart of 139 records developed by Clark and Stephenson (1979), and several later catalogues that made the overall record more complete.

Over the past 1,800 years, the authors identified "some nine cycles of solar brightness change," including the well-known Oort, Wolf, Sporer, Maunder, and Dalton Minima. With respect to the

Maunder Minimum—which occurred between 1645 and 1715 and is widely acknowledged to have been responsible for some of the coldest weather of the Little Ice Age—they report the temperatures of that period "were about one-half of a degree Celsius lower than the mean for the 1970s, consistent with the decrease in the decadal average solar irradiance." The Dalton Minimum occurred roughly between 1799 and 1820, with another dip in Northern Hemispheric temperatures. Since then, the authors state, "the Sun has gradually brightened" and "we are now in the Modern Maximum," which is likely responsible for the warmth of the Current Warm Period.

Although the long-term variations in solar brightness Pang and Yau identified "account for less than 1% of the total irradiance, there is clear evidence that they affect the Earth's climate." The authors' plot of total solar irradiance and Northern Hemispheric temperature from 1620 to the present (their Fig. 1c) indicates the former parameter (when appropriately scaled but without reference to any specific climate-change mechanism) can account for essentially all of the net change experienced by the latter parameter up to about 1980. After that time, the IPCC surface air temperature record rises dramatically, although radiosonde and satellite temperature histories largely match what would be predicted from the solar irradiance record. These facts could be interpreted as new evidence of the inaccuracy of the IPCC temperature history.

Rohling *et al*. (2003) "narrow down" temporal constraints on the millennial-scale variability of climate evident in ice-core δ^{18}O records by "determining statistically significant anomalies in the major ion series of the GISP2 ice core," after which they conduct "a process-oriented synthesis of proxy records from the Northern Hemisphere." With respect to the temporal relationships among various millennial-scale oscillations in Northern Hemispheric proxy climate records, the authors conclude a "compelling case" can be made for their being virtually in-phase, based on "the high degree of similarity in event sequences and structures over a very wide spatial domain," and "the fact that our process-oriented synthesis highlights a consistent common theme of relative dominance shifts between winter-type and summer-type conditions, ranging all the way across the Northern Hemisphere from polar into monsoonal latitudes." These findings, they additionally note, "corroborate the in-phase relationship between climate variabilities in the high northern latitudes and the tropics suggested in Blunier *et al*. (1998) and Brook *et al*. (1999)."

Although individual cycles of the persistent climatic oscillation "appear to have different intensities and durations," Rohling *et al.* further note, "a mean periodicity appears around ~1500 years (Mayewski *et al*., 1997; Van Kreveld *et al*., 2000; Alley *et al*., 2001)." They further report "this cycle seems independent from the global glaciation state (Mayewski *et al*., 1997; Bond *et al*., 1999)," and "^{10}Be and delta ^{14}C records may imply a link with solar variability (Mayewski *et al*., 1997; Bond *et al*., 2001)."

Usoskin *et al*. (2003) point out "sunspots lie at the heart of solar active regions and trace the emergence of large-scale magnetic flux, which is responsible for the various phenomena of solar activity" that may influence Earth's climate. They also state, "the sunspot number (SN) series represents the longest running direct record of solar activity, with reliable observations starting in 1610, soon after the invention of the telescope." The authors compared SN data with the millennial-scale temperature reconstruction of Mann *et al*. (1999) by extending the directly measured SN record back in time to AD 850 using records of ^{10}Be cosmonuclide concentration derived from polar ice cores. In doing so, they employed detailed physical models "developed for each individual link in the chain connecting the SN with the cosmogenic isotopes," and they combined these models in such a way that "the output of one model [became] the input for the next step."

The resulting reconstructed SN history of the past millennium behaved very much like the infamous "hockey stick" temperature history of Mann *et al*. (1999). It slowly declined over the entire time period—with numerous modest oscillations associated with well-known solar maxima and minima—until the end of the Little Ice Age, whereupon it rose dramatically. Usoskin *et al*. report, for example, "while the average value of the reconstructed SN between 850 and 1900 is about 30, it reaches values of 60 since 1900 and 76 since 1944." In addition, they report "the largest 100-year average of the reconstructed SN prior to 1900 is 44, which occurs in 1140–1240, i.e., during the medieval maximum," but they note "even this is significantly less than the level reached in the last century." Thus they conclude "the high level of solar activity since the 1940s is unique since the year 850."

References

Alley, R.B., Anandakrishnan, S., and Jung, P. 2001. Stochastic resonance in the North Atlantic. *Paleoceanography* **16**: 190–198.

Björck, S., Muscheler, R., Kromer, B., Andresen, C.S., Heinemeier, J., Johnsen, S.J., Conley, D., Koc, N., Spurk, M., and Veski, S. 2001. High-resolution analyses of an early Holocene climate event may imply decreased solar forcing as an important climate trigger. *Geology* **29**: 1107–1110.

Blunier, T., Chapellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., and Johnsen, S.J. 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature* **394**: 739–743.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G.C., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G., and Johnson, S. 1999. The North Atlantic's 1-2kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger cycles and the little ice age. In: Clark, P.U., Webb, R.S., and Keigwin, L.D. (Eds.) *Mechanisms of Global Climate Change at Millennial Time Scales*. American Geophysical Union *Geophysical Monographs* **112**: 35–58.

Brook, E.J., Harder, S., Severinghaus, J., and Bender, M. 1999. Atmospheric methane and millennial-scale climate change. In: Clark, P.U., Webb, R.S., and Keigwin, L.D. (Eds.) *Mechanisms of Global Climate Change at Millennial Time Scales*. American Geophysical Union *Geophysical Monographs* **112**: 165–175.

Clark, D.H. and Stephenson, F.R. 1979. A new revolution in solar physics. *Astronomy* **7**(2): 50–54.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., and Prentice, M. 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research* **102**: 26,345–26,366.

Oppo, D.W., McManus, J.F., and Cullen, J.L. 1998. Abrupt climate events 500,000 to 340,000 years ago: Evidence from subpolar North Atlantic sediments. *Science* **279**: 1335–1338.

Pang, K.D. and Yau, K.K. 2002. Ancient observations link changes in Sun's brightness and Earth's climate. *EOS: Transactions, American Geophysical Union* **83**: 481, 489–490.

Raymo, M.E., Ganley, K., Carter, S., Oppo, D.W., and McManus, J. 1998. Millennial-scale climate instability during the early Pleistocene epoch. *Nature* **392**: 699–702.

Rohling, E.J., Mayewski, P.A., and Challenor, P. 2003. On the timing and mechanism of millennial-scale climate variability during the last glacial cycle. *Climate Dynamics* **20**: 257–267.

Usoskin, I.G., Solanki, S.K., Schussler, M., Mursula, K., and Alanko, K. 2003. Millennium-scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s. *Physical Review Letters* **91**: 10.1103/PhysRevLett.91.211101.

Van Kreveld, S., Sarnthein, M., Erlenkeuser, H., Grootes, P., Jung, S., Nadeau, M.J., Pflaumann, U., and Voelker, A. 2000. Potential links between surging ice sheets, circulation changes, and the Dansgaard-Oeschger cycles in the Irminger Sea, 60-18 kyr. *Paleoceanography* **15**: 425–442.

Yau, K.K.C. 1988. A revised catalogue of Far Eastern observations of sunspots (165 B.C. to A.D. 1918). *Quarterly Journal of the Royal Astronomical Society* **29**: 175–197.

Zhuang, W.F. and Wang, L.Z. 1988. *Union Compilation of Ancient Chinese Records of Celestial Phenomena*. Jiangsu Science and Technology Press, Jiangsu Province, China.

3.3.3 North America

Wiles *et al*. (2004) derived a composite Glacier Expansion Index (GEI) for Alaska based on "dendrochronologically derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens," after which they compared this history of glacial activity with "the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability" and the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

The researchers found Alaska ice expansions "approximately every 200 years, compatible with a solar mode of variability," specifically, the de Vries 208-year solar cycle; by merging this cycle with the cyclical behavior of the PDO, Wiles *et al.* obtained a dual-parameter forcing function even better correlated with the Alaskan composite GEI, with major glacial advances clearly associated with the Sporer, Maunder, and Dalton solar minima.

Wiles *et al*. note "increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries." They make no mention of possible CO_2-induced global warming in discussing their results; Alaskan glacial activity "has been shown to be primarily a record of summer temperature change (Barclay *et al*., 1999)" and appears to be sufficiently well explained by solar and PDO variability alone. Four years later, Wiles *et al*. (2008) reconfirmed this solar-climate link in Alaska.

Regarding the nearby Columbia Icefield area of the Canadian Rockies, Luckman and Wilson (2005) used new tree-ring data to update a millennial temperature reconstruction for this region published in 1997. Their update employed different standardization techniques, such as the regional curve standardization method, in an effort to capture a greater degree of low frequency variability (centennial to millennial scale) than reported in the initial study. The new data set added more than one hundred years to the chronology and now covers the period AD 950–1994.

The updated proxy indicator of temperature showed considerable decadal- and centennial-scale variability, where generally warmer conditions prevailed during the eleventh and twelfth centuries, during approximately AD 1350–1450, and from about 1875 through the end of the record. Persistent cold conditions prevailed in 1200–1350, 1450–1550, and 1650–1850, with the 1690s being exceptionally cold (more than 0.4°C colder than the other intervals).

According to Luckman and Wilson, the Columbia Icefield reconstruction "appears to indicate a reasonable response of local trees to large-scale forcing of climates, with reconstructed cool conditions comparing well with periods of known low solar activity," which suggests the Sun is the main driver of these low frequency temperature trends.

Barron and Bukry (2007) extracted sediment cores from three sites on the eastern slope of the Gulf of California and, by examining these high-resolution records of diatoms and silicoflagellate assemblages, reconstructed sea surface temperatures there over the past 2,000 years. In all three of the sediment cores, the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures) was found to be greater during the Medieval Warm Period than at any other time over the 2,000-year period studied. During the Current Warm Period the diatom's relative abundance was lower than the 2,000-year mean, also in all three of the sediment cores. In addition, the first of the cores exhibited elevated *A. nodulifera* abundances from the start of the record to about AD 350, during the latter part of the Roman Warm Period, as well as between AD 1520 and 1560.

By analyzing radiocarbon production data, Barron and Bukry determined "intervals of increased radiocarbon production (sunspot minima) correlate with intervals of enhanced biosilica productivity," leading the two authors to conclude "solar forcing played a major role in determining surface water conditions in the Gulf of California during the past 2000 yr." They note "reduced solar irradiance (sunspot minima) causes cooling of winter atmospheric temperatures above the southwest US" and "this strengthens the atmospheric low and leads to intensification of northwest winds blowing down the Gulf, resulting in increased overturn of surface waters, increased productivity, and cooler SST."

Nederbragt and Thurow (2005) examined a high resolution marine sediment core taken from the Santa Barbara Basin (SBB) to determine whether millennial-scale climate cycles observed in the Atlantic Ocean were also present in the Pacific Ocean. Cross-spectral analyses revealed the presence of two dominant millennial-scale cycles in both the North Atlantic and Pacific SBB sedimentary records at frequencies of ~1000 and 2750 years. They also demonstrated these frequencies are similar to frequencies derived from a record of atmospheric Delta^{14}C typically used as an indicator of solar activity. The coherence between the North Atlantic, Pacific SBB, and atmospheric Delta^{14}C records strongly suggests, in the words of the authors, that "part of the climate variability during the Holocene is the result of variation in solar irradiance as an external forcing mechanism."

Richey *et al.* (2007) constructed "a continuous decadal-scale resolution record of climate variability over the past 1400 years in the northern Gulf of Mexico" from a box core recovered in the Pigmy Basin, northern Gulf of Mexico [27°11.61'N, 91°24.54'W], based on "paired analyses of Mg/Ca and $\delta^{18}O$ in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages." They report "two multi-decadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm or warmer than near-modern conditions between 1000 and 1400 yr B.P.," while "foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was 2–2.5°C below modern SST." In addition, they found "four minima in the Mg/Ca record between 900 and 250 yr. B.P. correspond with the Maunder, Sporer, Wolf, and Oort sunspot minima," providing additional evidence the historic warmth of Earth's past was likely solar-induced.

Poore *et al*. (2003) developed a 14,000-year record of Holocene climate based primarily on the relative abundance of the planktic foraminifer *Globigerinoides sacculifer* found in two sediment cores. In reference to North Atlantic millennial-scale cool events 1–7 identified by Bond *et al*. (2001) as belonging to a pervasive climatic oscillation with a period of approximately 1,500 years, Poore *et al*. report distinct excursions to lower abundances of *G. sacculifer* "match within 200 years the ages of Bond events 1–6," noting "major cooling events detected in the subpolar North Atlantic can be recognized in the GOM record." They additionally note "the GOM record includes more cycles than can be explained by a quasiperiodic 1500-year cycle," but such centennial-scale cycles with periods ranging from 200 to 500 years are also observed in the study of Bond *et al*. They note further their results "are in agreement with a number of studies indicating the presence of substantial century-scale variability in Holocene climate records from different areas," specifically citing the reports of Campbell *et al*. (1998), Peterson *et al*. (1991), and Hodell *et al*. (2001). They also discuss evidence that leads them to conclude "some of the high-frequency variation (century scale) in *G. sacculifer* abundance in our GOM records is forced by solar variability."

Lund and Curry (2004) analyzed a planktonic foraminiferal δ^{18}O time series obtained from three well-dated sediment cores retrieved from the seabed near the Florida Keys (24.4°N, 83.3°W) covering the past 5,200 years. As they describe it, isotopic data from the three cores "indicate the surface Florida Current was denser (colder, saltier or both) during the Little Ice Age than either the Medieval Warm Period or today" and "when considered with other published results (Keigwin, 1996; deMenocal *et al*., 2000), it is possible that the entire subtropical gyre of the North Atlantic cooled during the Little Ice Age, ... perhaps consistent with the simulated effects of reduced solar irradiance (Rind and Overpeck, 1993; Shindell *et al*., 2001)." In addition, they report "the coherence and phasing of atmospheric ^{14}C production and Florida Current δ^{18}O during the Late Holocene implies that solar variability may influence Florida Current surface density at frequencies between 1/300 and 1/100 years."

A 2012 study found temperatures along the coast of Cape Hatteras pulsated according to the rhythm of the 1,000-year solar cycle (Cléroux *et al*., 2012). The climate of British Columbia also has been driven by solar activity changes over the past 11,000 years (Gavin *et al*., 2012).

Li *et al*. (2006) "recovered a 14,000-year mineral-magnetic record from White Lake (~41°N, 75°W), a hardwater lake containing organic-rich sediments in northwestern New Jersey, USA." A comparison of the White Lake data with climate records from the North Atlantic sediments "shows that low lake levels at ~1.3, 3.0, 4.4, and 6.1 ka [1000 years before present] in White Lake occurred almost concurrently with the cold events at ~1.5, 3.0, 4.5, and 6.0 ka in the North Atlantic Ocean (Bond *et al*., 2001)" and "these cold events are associated with the 1500-year warm/cold cycles in the North Atlantic during the Holocene" that have "been interpreted to result from solar forcing (Bond *et al*., 2001)."

Long periods of warmth forced by variable solar activity in North America have occurred over and over again throughout the Holocene and beyond (Oppo *et al*., 1998; Raymo *et al*., 1998), suggesting the Current Warm Period also was instigated by this recurring phenomenon, not the CO_2 output of the Industrial Revolution.

References

Barclay, D.J., Wiles, G.C., and Calkin, P.E. 1999. A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska. *The Holocene* **9**: 79–84.

Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* **62**: 115–139.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Campbell, I.D., Campbell, C., Apps, M.J., Rutter, N.W., and Bush, A.B.G. 1998. Late Holocene ca.1500 yr climatic periodicities and their implications. *Geology* **26**: 471–473.

Cléroux, C., Debret, M., Cortijo, E., Duplessy, JH.-C., Dewilde, F., Reijmer, J., and Massei, N. 2012. High-resolution sea surface reconstructions off Cape Hatteras over the last 10 ka. *Paleoceanography* **27**: PA1205.

Cook, E.R. 2002. Reconstructions of Pacific decadal variability from long tree-ring records. *EOS: Transactions, American Geophysical Union* **83**: S133.

deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M. 2000. Coherent high- and low-latitude variability during the Holocene warm period. *Science* **288**: 2198–2202.

Gavin, D. G., Henderson, A. C. G., Westover, K. S., Fritz, S. C., Walker, I. R., Leng M. J., and Hu, F.S. 2011. Abrupt Holocene climate change and potential response to solar forcing in western Canada. *Quaternary Science Reviews* **30**: 1243–1255.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1370.

Keigwin, L. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.

Li, Y.-X., Yu, Z., Kodama, K.P., and Moeller, R.E. 2006. A 14,000-year environmental change history revealed by mineral magnetic data from White Lake, New Jersey, USA. *Earth and Planetary Science Letters* **246**: 27–40.

Luckman, B.H. and Wilson, R.J.S. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics* **24**: 131–144.

Lund, D.C. and Curry, W.B. 2004. Late Holocene variability in Florida Current surface density: Patterns and possible causes. *Paleoceanography* **19**: 10.1029/2004 PA001008.

Nederbragt, A.J. and Thurow, J. 2005. Geographic coherence of millennial-scale climate cycles during the Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **221**: 313–324.

Oppo, D.W., McManus, J.F., and Cullen, J.L. 1998. Abrupt climate events 500,000 to 340,000 years ago: Evidence from subpolar North Atlantic sediments. *Science* **279**: 1335–1338.

Peterson, L.C., Overpeck, J.T., Kipp, N.G., and Imbrie, J. 1991. A high-resolution Late Quaternary upwelling record from the anoxic Cariaco Basin, Venezuela. *Paleoceanography* **6**: 99–119.

Poore, R.Z., Dowsett, H.J., Verardo, S., and Quinn, T.M. 2003. Millennial- to century-scale variability in Gulf of Mexico Holocene climate records. *Paleoceanography* **18**: 10.1029/2002PA000868.

Raymo, M.E., Ganley, K., Carter, S., Oppo, D.W., and McManus, J. 1998. Millennial-scale climate instability during the early Pleistocene epoch. *Nature* **392**: 699–702.

Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.

Rind, D. and Overpeck, J. 1993. Hypothesized causes of decade- to century-scale climate variability: Climate model results. *Quaternary Science Reviews* **12**: 357–374.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., and Waple, A. 2001. Solar forcing of regional climate during the Maunder Minimum. *Science* **294**: 2149–2152.

Wiles, G.C., Barclay, D.J., Calkin, P.E., and Lowell, T.V. 2008. Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of Southern Alaska. *Global and Planetary Change* **60**: 115–125.

Wiles, G.C., D'Arrigo, R.D., Villalba, R., Calkin, P.E., and Barclay, D.J. 2004. Century-scale solar variability and Alaskan temperature change over the past millennium. *Geophysical Research Letters* **31**: 10.1029/2004GL020050.

3.3.4 South America

Nordemann *et al*. (2005) examined tree rings from species sensitive to fluctuations in temperature and precipitation throughout the southern region of Brazil and Chile, along with sunspot data, via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding of the effects of solar activity, climate, and geophysical phenomena on the continent of South America, where the time interval covered by the tree-ring samples from Brazil was 200 years and that from Chile was 2,500 years. Results of the spectral analysis revealed periodicities in the tree rings that corresponded well with the DeVries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles, while wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Utilizing a lichenometric method for dating glacial moraines, the Bolivian and French research team of Rabatel *et al*. (2005) developed "the first detailed chronology of glacier fluctuations in a tropical area during the Little Ice Age," focusing on fluctuations of the Charquini glaciers of the Cordillera Real in Bolivia, where they studied a set of 10 moraines that extend below the present glacier termini. The researchers determined the maximum glacier extension in Bolivia "occurred in the second half of the 17th century, as observed in many mountain areas of the Andes and the Northern Hemisphere." In addition, they found "this expansion has been of a comparable magnitude to that observed in the Northern Hemisphere, with the equilibrium line altitude depressed by 100–200 m during the glacier maximum." They say "the synchronization of glacier expansion with the Maunder and Dalton minima supports the idea that solar activity could have cooled enough the tropical atmosphere to provoke this evolution."

As for the magnitude and source of the cooling in the Bolivian Andes during the Little Ice Age, three years later Rabatal *et al*. (2008) estimated it to have been 1.1 to 1.2°C below that of the present, once again noting there was a "striking coincidence between the glacier expansion in this region of the tropics and the decrease in solar irradiance: the so-called 'Maunder minimum' (AD 1645-1715) during which irradiance might have decreased by around 0.24% (Lean and Rind, 1998) and could have resulted in an atmospheric cooling of 1°C worldwide (Rind *et al*., 2004)."

Glasser *et al*. (2004) analyzed a large body of evidence related to glacier fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte (47°00'S, 73°39'W) and the Hielo Patagonico Sur (between 48°50'S and 51°30'S). The glacial advancements that occurred during the cold interval preceding the Roman Warm Period are "part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al*., 1998; Wasson and Claussen, 2002), which coincides with an abrupt decrease in solar activity"; they add this observation "led van Geel *et al*. (2000) to suggest that variations in solar irradiance are more important as a driving force in variations in climate than previously believed."

With respect to the most recent recession of Hielo Patagonico Norte outlet glaciers from their late historic moraine limits at the end of the nineteenth century, Glasser *et al*. say "a similar pattern can be observed in other parts of southern Chile (e.g., Kuylenstierna *et al*., 1996; Koch and Kilian, 2001)." They note "in areas peripheral to the North Atlantic and in central Asia the available evidence shows that glaciers underwent significant recession at this time (cf. Grove, 1988; Savoskul, 1997)," which again suggests a globally distributed forcing factor such as cyclically variable solar activity.

Studying a bog, as opposed to a glacier, Chambers *et al*. (2007) presented new proxy climate data obtained from the Valle de Andorra northeast of Ushuaia, Tierra del Fuego, Argentina. These data, they emphasize, are "directly comparable" with similar proxy climate data obtained in numerous studies conducted in European bogs, "as they were produced using identical laboratory methods." Chambers *et al*. say their South American data show "a major climate perturbation at the same time as in northwest Europe," which they describe as "an abrupt climate cooling" that occurred approximately 2,800 years ago. They write, "its timing, nature and apparent global synchronicity lend support to the notion of solar forcing of past climate change, amplified by oceanic circulation."

Noting "rapid, high-magnitude climate changes might be produced within the Holocene by an inferred decline in solar activity (van Geel *et al*., 1998, 2000, 2003; Bond *et al*., 2001; Blaauw *et al*., 2004; Renssen *et al*., 2006)," the five European researchers conclude this "has implications for rapid, high-magnitude climate changes of the opposite direction—climatic warmings, possibly related to increases in solar activity." They further note "for the past 100 years any solar influence would for the most part have been in the opposite direction (i.e., to help generate a global climate warming) to that inferred for c. 2800–2710 cal. BP." They conclude this observation "has implications for interpreting the relative contribution of climate drivers of recent 'global warming.'"

Polissar *et al*. (2006) worked with data derived from sediment records of two Venezuelan watersheds along with ancillary data obtained from other studies conducted in the same general region. They developed continuous decadal-scale histories of glacier activity and moisture balance in a part of the tropical Andes (the Cordillera de Merida) over the past millennium and a half, from which they deduced contemporary histories of regional temperature and precipitation.

The international (Canada, Spain, United States, Venezuela) team of scientists writes, "comparison of the Little Ice Age history of glacier activity with reconstructions of solar and volcanic forcing suggest that solar variability is the primary underlying cause of the glacier fluctuations," because "the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and δ^{14}C measurements"; "spectral analysis shows significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, closely matching the de Vries and Gleissberg oscillations identified from solar irradiance reconstructions"; and "solar and volcanic forcing are uncorrelated between AD 1520 and 1650, and the magnetic susceptibility record follows the solar-irradiance reconstruction during this interval." In addition, they note "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima" and "temperature declines of -3.2 ± 1.4°C and precipitation increases of ~20% are required to produce the observed glacial responses."

Polissar *et al.* say their results "suggest considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability."

References

Blaauw, M., van Geel, B., and van der Plicht, J. 2004. Solar forcing of climate change during the mid-Holocene: indications from raised bogs in The Netherlands. *The Holocene* **14**: 35–44.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Chambers, F.M., Mauquoy, D., Brain, S.A., Blaauw, M., and Daniell, J.R.G. 2007. Globally synchronous climate change 2800 years ago: Proxy data from peat in South America. *Earth and Planetary Science Letters* **253**: 439–444.

Glasser, N.F., Harrison, S., Winchester, V., and Aniya, M. 2004. Late Pleistocene and Holocene palaeoclimate and glacier fluctuations in Patagonia. *Global and Planetary Change* **43**: 79–101.

Grosjean, M., Geyh, M.A., Messerli, B., Schreier, H., and Veit, H. 1998. A late-Holocene (<2600 BP) glacial advance in the south-central Andes (29°S), northern Chile. *The Holocene* **8**: 473–479.

Grove, J.M. 1988. *The Little Ice Age*. Routledge, London, UK.

Koch, J. and Kilian, R. 2001. Dendroglaciological evidence of Little Ice Age glacier fluctuations at the Gran Campo Nevado, southernmost Chile. In: Kaennel Dobbertin, M. and Braker, O.U. (Eds.) *International Conference on Tree Rings and People*. Davos, Switzerland, p. 12.

Kuylenstierna, J.L., Rosqvist, G.C., and Holmlund, P. 1996. Late-Holocene glacier variations in the Cordillera Darwin, Tierra del Fuego, Chile. *The Holocene* **6**: 353–358.

Lean, J. and Rind, D. 1998. Climate forcing by changing solar radiation. *Journal of Climate* **11**: 3069–3094.

Nordemann, D.J.R., Rigozo, N.R., and de Faria, H.H. 2005. Solar activity and El-Niño signals observed in Brazil and Chile tree ring records. *Advances in Space Research* **35**: 891–896.

Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., and Bradley, R.S. 2006. Solar modulation of Little Ice Age climate in the tropical Andes. *Proceedings of the National Academy of Sciences USA* **103**: 8937–8942.

Rabatel, A., Francou, B., Jomelli, V., Naveau, P., and Grancher, D. 2008. A chronology of the Little Ice Age in the tropical Andes of Bolivia (16°S) and its implications for climate reconstruction. *Quaternary Research* **70**: 198–212.

Rabatel, A., Jomelli, V., Naveau, P., Francou, B., and Grancher, D. 2005. Dating of Little Ice Age glacier fluctuations in the tropical Andes: Charquini glaciers, Bolivia, 16°S. *Comptes Rendus Geoscience* **337**: 1311–1322.

Renssen, H., Goosse, H., and Muscheler, R. 2006. Coupled climate model simulation of Holocene cooling events: solar forcing triggers oceanic feedback. *Climate Past Discuss.* **2**: 209–232.

Rind, D., Shindell, D., Perlwitz, J., Lerner, J., Lonergan, P., Lean, J., and McLinden, C. 2004. The relative importance of solar and anthropogenic forcing of climate change between the Maunder minimum and the present. *Journal of Climate* **17**: 906–929.

Savoskul, O.S. 1997. Modern and Little Ice Age glaciers in "humid" and "arid" areas of the Tien Shan, Central Asia: two different patterns of fluctuation. *Annals of Glaciology* **24**: 142–147.

van Geel, B., Heusser, C.J., Renssen, H., and Schuurmans, C.J.E. 2000. Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis. *The Holocene* **10**: 659–664.

van Geel, B., van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M., Renssen, H., Reynaud-Farrera, I., and Waterbolk, H.T. 1998. The sharp rise of δ^{14}C ca. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* **40**: 535–550.

van Geel, B., van der Plicht, J., and Renssen, H. 2003. Major δ^{14}C excursions during the Late Glacial and early Holocene: changes in ocean ventilation or solar forcing of climate change? *Quaternary International* **105**: 71–76.

Wasson, R.J. and Claussen, M. 2002. Earth systems models: a test using the mid-Holocene in the Southern Hemisphere. *Quaternary Science Reviews* **21**: 819–824.

3.3.5 Asia

Bashkirtsev and Mashnich (2003), two scientists from the Institute of Solar-Terrestrial Physics of the Siberian Division of the Russian Academy of Sciences, note in the Russian journal *Geomagnetizm i Aeronomiya*, “a number of publications report that the anthropogenic impact on the Earth’s climate is an obvious and proven fact,” when in their opinion “none of the investigations dealing with the anthropogenic impact on climate convincingly argues for such an impact.”

They cite the work of Friis-Christensen and Lassen (1991), who first noted the close relationship (r = -0.95) between the length of the sunspot cycle and the surface air temperature of the Northern Hemisphere over the period 1861–1989, where “warming and cooling corresponded to short (~10 yr) and prolonged (~11.5 yr) solar cycles, respectively.” They also cite the work of Zherebtsov and Kovalenko (2000), who established a high correlation (r = 0.97) between “the average power of the solar activity cycle and the surface air temperature in the Baikal region averaged over the solar cycle.” These two findings, Bashkirtsev and Mashnich contend, “leave little room for the anthropogenic impact on the Earth’s climate.” In addition, they note “solar variations naturally explain global cooling observed in 1950–1970, which cannot be understood from the standpoint of the greenhouse effect, since CO_2 was intensely released into the atmosphere in this period,” citing the work of Dergachev and Raspopov (2000).

Bashkirtsev and Mashnich conduct wavelet-spectra and correlation analyses of Irkutsk and world air temperatures and Wolf number data for the period 1882–2000, finding periodicities of 22 (Hale cycle) and 52 (Fritz cycle) years and reporting “the temperature response of the air lags behind the sunspot cycles by approximately 3 years in Irkutsk and by 2 years over the entire globe.”

Noting one could thus expect the upper envelope of sunspot cycles to reproduce the global temperature trend, they created such a plot and found “the lowest temperatures in the early 1900s correspond to the lowest solar activity (weak cycle 14), the further temperature rise follows the increase in solar activity; the decrease in solar activity in cycle 20 is accompanied by the temperature fall [from 1950–1970], and the subsequent growth of solar activity in cycles 21 and 22 entails the temperature rise [of the past quarter century].”

Bashkirtsev and Mashnich conclude “it has become clear that the current sunspot cycle (cycle 23) is weaker than the preceding cycles (21 and 22)” and “solar activity during the subsequent cycles (24 and 25) will be, as expected, even lower,” noting “according to Chistyakov (1996, 2000), the minimum of the secular cycle of solar activity will fall on cycle 25 (2021–2026), which will result in the minimum global temperature of the surface air (according to our prediction).”

Vaganov *et al*. (2000) utilized tree-ring width as a proxy for temperature to examine temperature variations in Asia over the past 600 years. According to a graph of the authors’ data, temperatures in the Asian subarctic exhibited a small positive trend from the start of the record until about 1750. Thereafter, a severe cooling trend ensued, followed by a 130-year warming trend from about 1820 through 1950, after which temperatures fell once again. The authors state the amplitude of twentieth century warming “does not go beyond the limits of reconstructed natural temperature fluctuations in the Holocene subarctic zone.” They also report finding a significant correlation with solar radiation and volcanic activity over the entire 600-year period (R = 0.32 for solar radiation, R = -0.41 for volcanic activity), and this correlation actually improved over the shorter interval of the industrial period, 1800 to 1990 (R = 0.68 for solar radiation, R = -0.59 for volcanic activity).

In this region of the world, where climate models predict large increases in temperature as a result of the historical rise in the air’s CO_2 concentration, real-world data show a cooling trend since around 1940, when the greenhouse effect of CO_2 should have been most prevalent. Where warming does exist in the record (between about 1820 and 1940), much of it correlates with changes in solar irradiance and volcanic activity—two factors free of anthropogenic influence.

In two additional paleoclimate studies from the continental interior of Russia’s Siberia, Kalugin *et al.* (2005) and Kalugin *et al.* (2007) analyzed sediment cores from Lake Teletskoye in the Altai Mountains (51°42.90’N, 87°39.50’E) to produce multi-proxy climate records spanning the past 800 years. Analyses of the multi-proxy records revealed several distinct climatic periods over the past eight centuries. The regional climate was relatively warm, with high terrestrial productivity, from AD 1210 to 1380. Thereafter, temperatures cooled, reaching peak deterioration between 1660 and 1700, which, in the words of Kalugin *et al.* (2005), “corresponds to the age range of the well-known Maunder Minimum (1645–1715)” of solar sunspot activity.

Aono and Kazui (2008) developed an uninterrupted 1,100-year history of March mean temperature at Kyoto, Japan using phenological data on the times of full-flowering of cherry trees (*Prunus jamasakura*) acquired from old diaries and chronicles written at Kyoto. That record was reconciled with instrumental temperature measurements obtained over the period 1881–2005 and compared with the sunspot number history developed by Solanki *et al.* (2004).

The researchers report "the existence of four cold periods, 1330–1350, 1520–1550, 1670–1700, and 1825–1830, during which periods the estimated March mean temperature was 4–5°C, about 3–4°C lower than the present normal temperature," and "these cold periods coincided with the less extreme periods [of solar activity], known as the Wolf, Spoerer, Maunder, and Dalton minima, in the long-term solar variation cycle, which has a periodicity of 150–250 years." In addition, they report "a time lag of about 15 years was detected in the climatic temperature response to short-term solar variation."

Kitagawa and Matsumoto (1995) analyzed $\delta^{13}C$ variations of Japanese cedars growing on Yakushima Island (30°20'N, 130°30'E) in an effort to reconstruct a high-resolution proxy temperature record over the past two thousand years. In addition, they applied spectral analysis to the $\delta^{13}C$ time series in an effort to learn if any significant periodicities were present in the record. They found significant decadal to centennial-scale variability throughout the record, with temperatures fluctuating by about 5°C across the series. Between AD 700–1200 they found a 1°C rise in average temperature (pre-1850 average), which the authors state "appears to be related to the 'Medieval Warm Period.'" By contrast, temperatures were about 2°C below the long-term pre-1850 average during the multi-century Little Ice Age between AD 1580 and 1700. Kitagawa and Matsumoto also report finding significant temperature periodicities of 187, 89, 70, 55, and 44 years. Noting the 187-year cycle closely corresponds to the well-known Suess cycle of solar activity and the 89-year cycle compares well with the Gleissberg solar cycle, they conclude their findings provide further support for a Sun-climate relationship.

Ten years later, Cini Castagnoli *et al.* (2005) reexamined the Kitagawa and Matsumoto data set for evidence of recurring cycles using Singular Spectrum Analysis and Wavelet Transform, after which it was compared with a 300-year record of sunspots. Their analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity plus a second multi-decadal oscillation of about 87 years for the tree-ring series in phase with the amplitude modulation of the sunspot number series over the past 300 years. They concluded the overall phase agreement between the climate reconstruction and variation in the sunspot number series "favors the hypothesis that the [multi-decadal] oscillation" revealed in the record "is connected to the solar activity."

Several studies have documented a solar influence on temperature in China from several proxy temperature indicators. Paulsen *et al.* (2003) utilized high-resolution records of $\delta^{13}C$ and $\delta^{18}O$ from a stalagmite in Buddha Cave, central China [33°40'N, 109°05'E], to infer changes in climate over the past 1,270 years. Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." The data also revealed a number of other cycles superimposed on these major millennial-scale temperature cycles, which they attributed to cyclical solar and lunar phenomena.

Tan *et al.* (2004) established an annual layer thickness chronology for a stalagmite from Beijing Shihua Cave and reconstructed a 2,650-year (BC 665–AD 1985) warm season (MJJA: May, June, July, August) temperature record for Beijing by calibrating the thickness chronology with the observed MJJA temperature record (Tan *et al.*, 2003). The warm season temperature record was "consistent with oscillations in total solar irradiance inferred from cosmogenic ^{10}Be and ^{14}C" and "remarkably consistent with Northern Atlantic drift ice cycles that were identified to be controlled by the Sun through the entire Holocene [Bond *et al.*, 2001]." Both records clearly depict the start of the Current Warm Period, Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, Roman Warm Period, and the cold climate at the start of both records.

The authors conclude "the synchronism between the two independent Sun-linked climate records therefore suggests that the Sun may directly couple hemispherical climate changes on centennial to millennial scales." The cyclical nature of the millennial-scale oscillation of climate evident in both climate records suggests there is no need to invoke rising atmospheric CO_2 concentrations as a cause of the Current Warm Period.

Working with a stalagmite found in Wanxiang Cave (33°19'N, 105°00'E), Zhang *et al.* (2008) developed a $\delta^{18}O$ record with an average resolution of 2.5 years covering the period AD 190 to 2003. According to the 17 authors, the $\delta^{18}O$ record "exhibits a series of centennial to multi-centennial fluctuations broadly similar to those documented in Northern Hemisphere temperature reconstructions, including the Current Warm Period, Little Ice Age, Medieval Warm Period and Dark Age Cold Period."

In addition, Zhang *et al*. state the δ^{18}O record "correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes." In a commentary that accompanied Zhang *et al*.'s article, Kerr (2008) quotes other researchers calling the Zhang *et al*. record "amazing," "fabulous," and "phenomenal," noting it "provides the strongest evidence yet for a link among Sun, climate, and culture."

A team led by Professor ZhongHui Liu of Hong Kong University recently reported additional empirical evidence for solar forcing of temperatures around northern Tibetan Plateau, shown in Figure 3.3.5.1 below. The authors (He *et al*., 2013), writing in *Chinese Science Bulletin*, presented the alkenone-based reconstruction of temperatures, at decadal resolution, from Lake Gahai and Lake Sugan covering about 2,600 and 2,200 years, respectively. The estimated warmth of the MWP period is as much as 1.9°C warmer than the modern warm period. The temperature reconstruction makes clear the close relationship of the warm-cold variations with the changing solar activity levels over the same interval.

Hong *et al*. (2000) developed a 6,000-year high-resolution δ^{18}O record from plant cellulose deposited in a peat bog in the Jilin Province of China (42° 20' N, 126° 22' E), from which they inferred the temperature history of that location over the past six millennia. They compared this record with a previously derived δ^{14}C tree-ring record representative of the intensity of solar activity over this period.

The area was found to have been relatively cold between 4000 and 2600 BC, then warming until it reached the maximum warmth of the record in about 1600 BC, after which it fluctuated about this warm mean for approximately 2,000 years. Starting about AD 350, the climate began to cool, with the most dramatic cold associated with three temperature minima centered at about AD 1550, 1650, and 1750, corresponding to the most severe cold of the Little Ice Age.

The authors call attention to their finding of "an obvious warm period represented by the high δ^{18}O from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe." They also report "at that time, the northern boundary of the cultivation of citrus tree (*Citrus reticulata Blanco*) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, and it has been estimated that the annual mean temperature was 0.9-1.0°C higher than at present." Hong *et al*. also note "there is a remarkable, nearly one to one, correspondence between the changes of atmospheric δ^{14}C and the variation in δ^{18}O of the peat cellulose," which led them to conclude the temperature history of the past 6,000 years at the site of their study has been "forced mainly by solar variability."

Porter and Weijian (2006) analyzed 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers "represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation," while "brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate." They also report the climatic variations they discovered "correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water."

The researchers state "the correspondence of these records over the full span of Holocene time implies a close relationship between North Atlantic climate and the monsoon climate of central China." They also note the most recent of the episodic cold periods, which they identify as the Little Ice Age, began about AD 1370, while the preceding cold period ended somewhere in the vicinity of AD 810. Their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. Relating this millennial-scale climate cycle to the similar-scale drift-ice cycle of Bond *et al.* (2001) implies they accept solar forcing as the most likely cause of the alternating multi-century mild/moist and cold/dry periods of North-Central China.

Further evidence of a solar-climate link has been obtained from the Tibetan Plateau in China. Wang *et al*. (2002), for example, studied changes in δ^{18}O and NO_3^- in an ice core retrieved from the Guliya Ice Cap (35°17'N, 81°29'E), comparing their results with

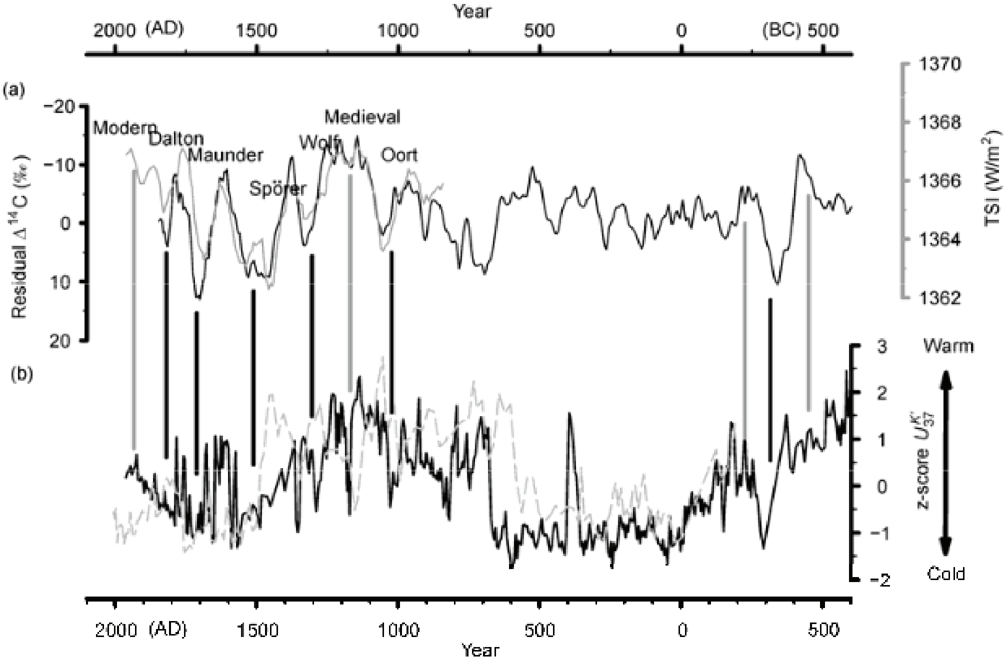

Figure 3.3.5.1. Correlations between solar activity proxies (top curves: TSI-grey; 14C-black) and temperature proxies (bottom curves: Lake Sugan-grey; Lake Gahai-black) from northern Tibetan Plateau. Reprinted with permission from He, Y.X., Liu, W.G., Zhao, C., Wang, Z., Wang, H.Y., Liu, Y., Qin, X.Y., Hu, Q.H., An, Z.S., and Liu, Z.H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

ancillary data from Greenland and Antarctica. Two cold events—a weak one around 9.6–9.2 thousand years ago (ka) and a strong one referred to as the "8.2 ka cold event"—were identified in the Guliya ice core record. The authors report these events occurred "nearly simultaneously with two ice-rafted episodes in the North Atlantic Ocean." They also note both events occurred during periods of weakened solar activity.

Remarking that evidence for the 8.2 ka cold event "occurs in glacial and lacustrine deposits from different areas," the authors say this evidence "suggests that the influence of this cold event may have been global." They also say "comprehensive analyses indicate that the weakening of solar insolation might have been the external cause of the '8.2 ka cold event'" and "the cause of the cold event around 9.6–9.2 ka was also possibly related to the weaker solar activity." The authors thus conclude these observations imply "millennial-scale climatic cyclicity might exist in the Tibetan Plateau as well as in the North Atlantic."

Xu *et al.* (2002) studied plant cellulose δ^{18}O variations in cores retrieved from peat deposits west of Hongyuan County at the northeastern edge of the Qinghai-Tibetan Plateau (32° 46'N, 102° 30'E). The authors report finding three consistently cold events centered at approximately 500, 700, and 900 AD, during what is sometimes referred to as the Dark Ages Cold Period. Then, for the period 1100–1300 AD, they report "the δ^{18}O of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the 'Medieval Warm Period.'" Finally, they note "the periods 1370–1400 AD, 1550–1610 AD, [and] 1780–1880 AD recorded three cold events, corresponding to the 'Little Ice Age.'"

Power spectrum analyses of their data revealed periodicities of 79, 88, and 123–127 years, "suggesting that the main driving force of Hongyuan climate change is from solar activities." In a subsequent paper by the same authors, Xu *et al.* (2006) compared the Hongyuan temperature variations with solar activity inferred from atmospheric ^{14}C and ^{10}Be concentrations measured in a South Pole ice core, after which they performed cross-spectral analyses to determine the relationship between temperature and solar variability, comparing their results with similar results obtained by other researchers.

Xu *et al*. (2006) report, “during the past 6000 years, temperature variations in China exhibit high synchrony among different regions, and importantly, are in-phase with those discovered in other regions in the northern hemisphere.” They also say their “comparisons between temperature variations and solar activities indicate that both temperature trends on centennial/millennial timescales and climatic events are related to solar variability.” The researchers conclude “quasi-100-year fluctuations of solar activity may be the primary driving force of temperature during the past 6000 years in China.”

Two years later Tan *et al*. (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau’s northeast margin since AD 960 based on an analysis of Chinese historical records, after which they compared the result with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories.

Tan *et al*. discovered “high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere.” Consequently, their precipitation record may be used to infer a Medieval Warm Period that stretched from approximately AD 960 to 1230, with temperature peaks in the vicinity of AD 1000 and 1215 that clearly exceeded the twentieth century peak temperature of the Current Warm Period. They also found “good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record.” These findings harmonize, in their words, with “numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene,” in support of which they attach 22 scientific references.

Tan *et al*. conclude the “synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity,” which apparently produced a Medieval Warm Period both longer and stronger than what has been experienced to date during the Current Warm Period in the northeast margin of the Tibetan Plateau.

Xu *et al*. (2008) studied decadal-scale temperature variations of the past six centuries derived from four high-resolution temperature indicators—the δ^{18}O and δ^{13}C of bulk carbonate, total carbonate content, and the detrended δ^{15}N of organic matter—extracted from Lake Qinghai (36°32’-37°15’N, 99°36’-100°47’E) on the northeast Qinghai-Tibet plateau, comparing the resultant variations with proxy temperature indices derived from nearby tree rings and reconstructed solar activity. The analysis revealed “four obvious cold intervals during the past 600 years at Lake Qinghai, namely 1430–1470, 1650–1715, 1770–1820 and 1920–1940,” and “these obvious cold intervals are also synchronous with the minimums of the sunspot numbers during the past 600 years,” namely, “the Sporer, the Maunder, and the Dalton minimums.” These facts strongly suggest, in their words, “that solar activities may dominate temperature variations on decadal scales at the northeastern Qinghai-Tibet plateau.”

If the development of the significant cold of the Little Ice Age was driven by a change in some type of solar activity, it logically follows that the global warming of the twentieth century was driven primarily by the reversal of that trend in solar activity, not by the historical rise in the air’s CO_2 content. However, as also noted by Xu *et al*., how small perturbations of solar activity have led “to the observed global warming, what is the mechanism behind it, etc., are still open questions.”

The authors write, “the middle reach of the Yangtze River possesses abundant depositional resources (e.g. stalagmite, peatland and lake sediments),” which “are reliable information carriers for paleoclimate and paleoenvironmental reconstruction.” They add “the reconstruction of long-term paleoclimate change would provide the premise for accurate prediction of the future.”

Soon *et al.* (2011) revealed a high degree of correlation between Chinese surface temperature records and two measures of solar radiation: a reconstruction of total solar irradiance (TSI) over the interval 1880–2002 (Figure 3.3.5.2) and a reconstruction of sunshine duration (Figure 3.3.5.3). The correlation between the data sets resembles an earlier correlation published by Soon (2005) between Arctic-wide surface temperature and TSI. Such strong correlations between temperature and solar-related indices from different geographical regions, together with the solar modulation of the Atlantic Meridional overturning circulation on multidecadal to centennial timescales (Soon, 2009), suggest solar forcing at the top of the atmosphere can and does persist to influence or drive climatic change near the surface of Earth. The simultaneous existence of the correlation between Chinese surface temperature with the two different measures of solar radiation may provide a

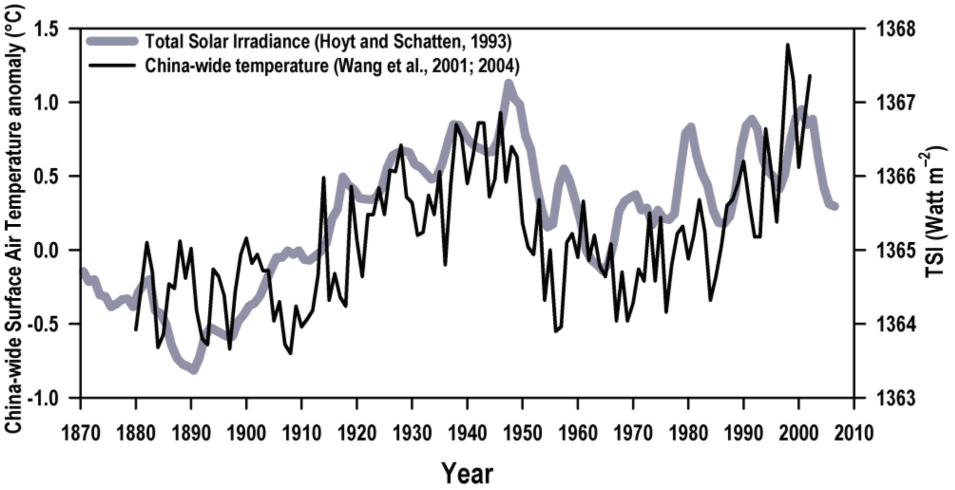

Figure 3.3.5.2. The empirical correlation between China-wide surface air temperature and estimated total solar irradiance from 1880 to 2002. Reprinted with permission from Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 2331–2344.

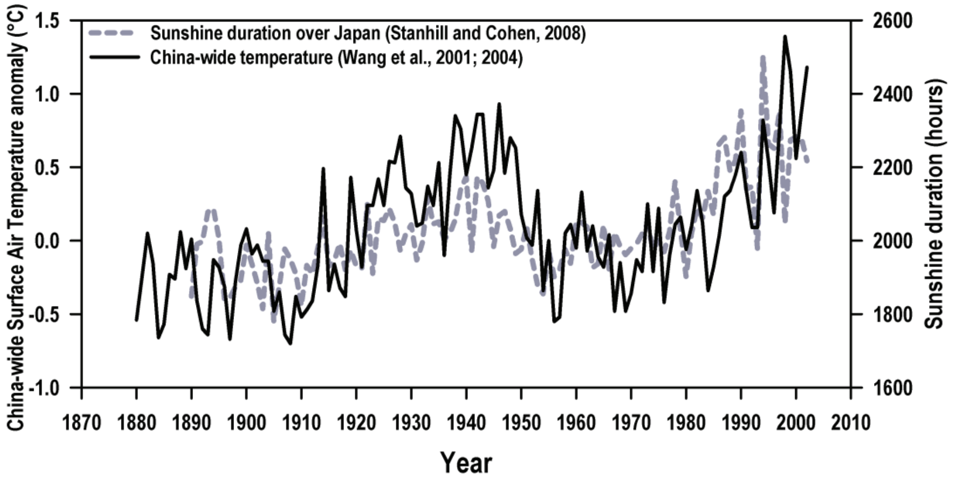

Figure 3.3.5.3. The empirical correlation between China-wide surface air temperature and the Japanese sunshine duration record from Stanhill and Cohen (2008) from 1890 to 2002. Also reprinted with permission from Soon *et al.* 2011.

strong physical constraint on how the Sun's irradiation can systematically modulate surface air temperature, at least in China.

Soon *et al.*'s work also explores the difficult challenge of having to explain how the transparency of the atmospheric column changes over time, through changing cloud fields and/or through more or less loading of particulate matters. According to the authors, the empirical results shown in their two figures reproduced here may be related to a key meteorological phenomenon involving the so-called Asian-African westerly jets, which Soon *et al.* (2011) say provide direct evidence to support a real physical Sun-climate link, as opposed to a mere statistical coincidence. A specific wave-5 or -6 pattern of circumglobal teleconnection among five or six regional centers of action is used to explain why the widely separated meteorological regimes and climatic zones are interconnected.

It is important to point out the enormous difficulties of modeling such empirical observations even using the best computer climate models of our day. It is not an exaggeration to say this one hurdle—not knowing how solar radiation propagates and changes from the top of the atmosphere to the near-surface or surface—has for at least the past 100 years prevented or slowed scientific progress into the Sun-climate connection.

Through phytolith analysis of a sediment core extracted at Zhoulao town in China's Jianli County in AD 2000, Gu *et al.* (2012) reconstructed a high-resolution record of paleoclimate change over the past 15,000 years in the middle reaches of the Yangtze River. They compared their results with paleoclimatic indicators derived from stalagmites, peatlands, North Atlantic deep-sea sediments (Bond *et al.*, 1997, 2001), the Loess Plateau of Central China, and Arabic Sea sediments. The five Chinese scientists identified eight climatic phases over the temperature reconstruction: the Last Glacial Maximum (20–14.8 cal ka BP), the Last Deglaciation (14.8–11.9 cal ka BP), a low temperature phase in the Early Holocene (11.9–8 cal ka BP), the Holocene Optimum (8–4.9 cal ka BP), the Holocene Katathermal (4.9–1.1 cal ka BP), the Medieval Warm Period (1.1–0.7 cal ka BP), the Little Ice Age (0.7–0.15 cal ka BP), and the Modern Warming (0.15 cal ka BP-present). In addition, they discovered the climate history of their research area had strong links with the contemporary histories of the Indian Summer Monsoon, the Asian Summer Monsoon, and the Holocene drift-ice events of the North Atlantic Ocean, which were discovered and described by Bond *et al.* (1997, 2001). Gu *et al.* conclude the correlation between their climate history and the Bond events "reveals that solar activity controls the Earth surface climate system at the centennial and millennial scales."

References

Aono, Y. and Kazui, K. 2008. Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century. *International Journal of Climatology* **28**: 905–914.

Bashkirtsev, V.S. and Mashnich, G.P. 2003. Will we face global warming in the nearest future? *Geomagnetiz i Aeronomija* **43**: 132–135.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Chezebiet, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial scale cycle in North-Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.

Chistyakov, V.F. 1996. On the structure of the secular cycles of solar activity. In: *Solar Activity and Its Effect on the Earth* (Chistyakov, V.F., Asst. Ed.), Dal'nauka, Vladivostok, Russia, pp. 98–105.

Chistyakov, V.F. 2000. On the Sun's radius oscillations during the Maunder and Dalton Minimums. In: *Solar Activity and Its Effect on the Earth* (Chistyakov, V.F., Asst. Ed.), Dal'nauka, Vladivostok, Russia, pp. 84–107.

Cini Castagnoli, G., Taricco, C., and Alessio, S. 2005. Isotopic record in a marine shallow-water core: Imprint of solar centennial cycles in the past 2 millennia. *Advances in Space Research* **35**: 504–508.

Dergachev, V.A. and Raspopov, O.M. 2000. Long-term processes on the Sun controlling trends in the solar irradiance and the Earth's surface temperature. *Geomagnetism and Aeronomy* **40**: 9–14.

Friis-Christensen, E. and Lassen, K. 1991. Length of the solar cycle: An indicator of solar activity closely associated with climate. *Science* **254**: 698–700.

Gu, Y., Wang, H., Huang, X., Peng, H., and Huang, J. 2012. Phytolith records of the climate change since the past 15000 years in the middle reach of the Yangtze River in China. *Frontiers of Earth Science* **6**: 10–17.

He, Y.X., Liu, W.G., Zhao, C., Wang, Z., Wang, H.Y., Liu, Y., Qin, X.Y., Hu, Q.H., An, Z.S., and Liu, Z.H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

Hong, Y.T., Jiang, H.B., Liu, T.S., Zhou, L.P., Beer, J., Li, H.D., Leng, X.T., Hong, B., and Qin, X.G. 2000. Response of climate to solar forcing recorded in a 6000-year δ^{18}O time-series of Chinese peat cellulose. *The Holocene* **10**: 1–7.

Kalugin, I., Daryin, A., Smolyaninova, L., Andreev, A., Diekmann, B., and Khlystov, O. 2007. 800-yr-long records of annual air temperature and precipitation over southern Siberia inferred from Teletskoye Lake sediments. *Quaternary Research* **67**: 400–410.

Kalugin, I., Selegei, V., Goldberg, E., and Seret, G. 2005. Rhythmic fine-grained sediment deposition in Lake Teletskoye, Altai, Siberia, in relation to regional climate change. *Quaternary International* **136**: 5–13.

Kerr, R.A. 2008. Chinese cave speaks of a fickle Sun bringing down ancient dynasties. *Science* **322**: 837–838.

Kitagawa, H. and Matsumoto, E. 1995. Climatic implications of δ^{13}C variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.

Paulsen, D.E., Li, H.-C., and Ku, T.-L. 2003. Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records. *Quaternary Science Reviews* **22**: 691–701.

Porter, S.C. and Weijian, Z. 2006. Synchronism of Holocene East Asian monsoon variations and North Atlantic drift-ice tracers. *Quaternary Research* **65**: 443–449.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schussler, M., and Beer, J. 2004. Unusual activity of the Sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.

Soon, W. W.-H. 2005. Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years. *Geophysical Research Letters* **32**:10.1029/2005GL023429

Soon, W. 2009. Solar Arctic-mediated climate variation on multidecadal to centennial timescales: Empirical evidence, mechanistic explanation, and testable consequences. *Physical Geography* **30**: 144–184.

Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 2331–2344.

Stanhill, G. and Cohen, S. 2008. Solar radiation changes in Japan during the 20th century: Evidence from sunshine duration measurements. *Journal of the Meteorological Society of Japan* **86**: 57−67.

Tan, L., Cai, Y., An, Z., and Ai, L. 2008. Precipitation variations of Longxi, northeast margin of Tibetan Plateau since AD 960 and their relationship with solar activity. *Climate of the Past* **4**: 19–28.

Tan, M., Hou, J., and Liu, T. 2004. Sun-coupled climate connection between eastern Asia and northern Atlantic. *Geophysical Research Letters* **31**: 10.1029/2003GL019085.

Tan, M., Liu, T.S., Hou, J., Qin, X., Zhang, H., and Li, T. 2003. Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature. *Geophysical Research Letters* **30**: 10.1029/2003GL017352.

Vaganov, E.A., Briffa, K.R., Naurzbaev, M.M., Schweingruber, F.H., Shiyatov, S.G., and Shishov, V.V. 2000. Long-term climatic changes in the arctic region of the Northern Hemisphere. *Doklady Earth Sciences* **375**: 1314–1317.

Wang, N., Yao, T., Thompson, L.G., Henderson, K.A., and Davis, M.E. 2002. Evidence for cold events in the early Holocene from the Guliya ice core, Tibetan Plateau, China. *Chinese Science Bulletin* **47**: 1422–1427.

Xu, H., Hong, Y.T., Lin, Q.H., Hong, B., Jiang, H.B., and Zhu, Y.X. 2002. Temperatures in the past 6000 years inferred from $\delta^{18}O$ of peat cellulose from Hongyuan, China. *Chinese Science Bulletin* **47**: 1578–1584.

Xu, H., Hong, Y., Lin, Q., Zhu, Y., Hong, B., and Jiang, H. 2006. Temperature responses to quasi-100-yr solar variability during the past 6000 years based on $\delta^{18}O$ of peat cellulose in Hongyuan, eastern Qinghai-Tibet plateau, China. *Palaeogeography, Palaeoclimatology, Palaeoecology* **230**: 155–164.

Xu, H., Liu, X., and Hou, Z. 2008. Temperature variations at Lake Qinghai on decadal scales and the possible relation to solar activities. *Journal of Atmospheric and Solar-Terrestrial Physics* **70**: 138–144.

Zhang, P., Cheng, H., Edwards, R.L., Chen, F., Wang, Y., Yang, X., Liu, J., Tan, M., Wang, X., Liu, J., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L., and Johnson, K.R. 2008. A test of climate, Sun, and culture relationships from an 1810-year Chinese cave record. *Science* **322**: 940–942.

Zherebtsov, G.A. and Kovalenko, V.A. 2000. Effect of solar activity on hydrometeorological characteristics in the Baikal region. *Proceedings of the International Conference "Solar Activity and Its Terrestrial Manifestations,"* Irkutsk, Russia, p. 54.

3.3.6 Europe

Holzhauser *et al.* (2005) presented high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, starting with an in-depth analysis of the Great Aletsch glacier, the largest glacier in the European Alps.

The three researchers report "during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today," noting "the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al*., 2003)." After an intervening unnamed cold-wet phase, during which the glacier grew in both mass and length, they find "during the Iron/Roman Age Optimum between c. 200 BC and AD 50," better known as the Roman Warm Period, the glacier again retreated and "reached today's extent or was even somewhat shorter than today." Their records also identified the Dark Ages Cold Period, followed by "the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300," a cold-wet phase "characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60," after which the glacier began its latest and still-ongoing recession in 1865. Holzhauser *et al*. also note written documents from the fifteenth century AD indicate at some time during that hundred-year interval "the glacier was of a size similar to that of the 1930s."

Data pertaining to the Gorner glacier (the second largest in the Swiss Alps) and Lower Grindelwald glacier of the Bernese Alps tell much the same story, as Holzhauser *et al*. report these glaciers and the Great Aletsch glacier "experienced nearly synchronous advances" throughout the study period. The Swiss and French scientists report "glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity," which in their estimation "suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlén, 1973; Magny, 1993; van Geel *et al*., 1996; Bond *et al*., 2001)." They conclude by stating "a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene."

Hormes *et al*. (2006) determined radiocarbon dates of 71 samples of wood and peat found in the basal shear planes and proglacial outwashes of eight mid-latitude glaciers in the Central Swiss Alps. They found the dates clustered within discrete time intervals and were able to specify periods during which the glaciers' leading edges were less extended than during the 1990s. "The glaciers investigated were less extensive than during the 1990s, with a shorter length during several defined periods," they noted. These defined periods were: 10,110–9,550, 9,210–7,980, 7,450–6,500, 6,370–5,950, 5,860–3,360, 2,940–2,620 and 2,500–1,170 years before present. They also report "some of these periods with reduced glacier lengths are also documented on Svalbard in the Arctic, the Subantarctic Kerguelen islands in the Indian Ocean, and in Scandinavia." They point out "the defined radiocarbon-dated periods with less extensive glaciers coincide well with periods of reduced ^{14}C production, pointing to the Sun's role in glacier variation processes."

Mauquoy *et al*. (2002a) extracted peat monoliths from ombrotrophic mires at Lille Vildmose, Denmark (56°50'N, 10°15'E) and Walton Moss, UK (54°59'N, 02°46'W), sites which, being separated by about 800 km, "offer the possibility of detecting supraregional changes in climate." From these monoliths, vegetative macrofossils were extracted at contiguous 1-cm intervals and examined using light microscopy. Where increases in the abundances of *Sphagnum tenellum* and *Sphagnum cuspidatum* were found, a closely spaced series of ^{14}C AMS-dated samples immediately preceding and following each increase was used to "wiggle-match" date them (van Geel and Mook, 1989), enabling comparison of the climate-induced shifts with the history of ^{14}C production during the Holocene.

The work revealed a climatic deterioration that marked the beginning of a period of inferred cool, wet conditions that correspond fairly closely with the Wolf, Sporer, and Maunder Minima of solar activity, as manifest in contemporary δ^{14}C data. The authors report "these time intervals correspond to periods of peak cooling in 1000-year Northern Hemisphere climate records," adding to the "increasing body of evidence" that "variations in solar activity may well have been an important factor driving Holocene climate change."

Two years later, Mauquoy *et al*. (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes of climate change during the Holocene. The authors state "analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al*. (1995), van Geel *et al*. (1996), Speranza *et al*. (2000), Speranza (2000) and Mauquoy *et al*. (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977)." This close correspondence suggests "changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al*., 1996, 1998, 1999, 2000) and the 'Little Ice Age' series of palaeoclimatic changes."

Berstad *et al*. (2003) used a marine sediment core retrieved from the southern Norwegian continental margin to reconstruct sea surface temperatures (SSTs) from δ^{18}O data derived from the remains of the planktonic foraminifera species *Neogloboquadrina pachyderma* (summer temperatures) and *Globigerina bulloides* (spring temperatures). Among other things, the authors' work depicts a clear connection between the cold temperatures of the Little Ice Age and the reduced solar activity of the Maunder and Sporer solar minima, as well as between the warm temperatures of the most recent 70 years and the enhanced solar activity of the Modern solar maximum. The researchers clearly imply a causative connection between the SSTs and solar activity, as is also implied by the recent sunspot number reconstruction of Usoskin *et al*. (2003).

Sejrup *et al*. (2010) used two sediment cores extracted from the seabed of the eastern Norwegian Sea (~64°N, 3°E) to develop a 1,000-year proxy temperature record "based on measurements of δ^{18}O in *Neogloboquadrina pachyderma* (dextral form), a planktonic foraminifer that calcifies at relatively shallow depths within the Atlantic waters of the eastern Norwegian Sea during late summer," which they compared with the temporal histories of various proxies of solar activity. The authors point out "the proxy record of solar variability from cosmogenic nuclides and telescopic observations of sunspots explains a substantial fraction of reconstructed Northern Hemisphere temperature variability during the pre-Industrial portion of the last millennium, with a simulated range of up to 0.4°C for plausible irradiance scaling and climate sensitivity," citing Crowley (2000) and Ammann *et al*. (2007). They add, "at both the intra- and supra-decadal timescales there appear to be regional responses to solar forcing that are significantly larger than the global or hemisphere-scale response," citing Shindell *et al*. (2001), Woods and Lean (2007), and Tung and Camp (2008).

Sejrup *et al*.'s analysis revealed "the lowest isotope values (highest temperatures) of the last millennium are seen ~1100–1300 A.D., during the Medieval Climate Anomaly, and again after ~1950 A.D." In between these warm intervals were the colder temperatures of the Little Ice Age, when lower temperatures (thermal minima) occurred at the times of the Dalton, Maunder, Sporer and Wolf solar minima, such that the δ^{18}O proxy record of near-surface water temperature was found to be "robustly and near-synchronously correlated with various proxies of solar variability spanning the last millennium," with decade- to century-scale temperature variability of 1 to 2°C revealing the Sun outshined nearly all other forcings of climate change in this region of Earth over the past millennium.

Haltia-Hovi *et al*. (2007) extracted sediment cores from beneath the 0.7-m-thick ice platform on Lake Lehmilampi (63°37'N, 29°06'E) in North Karelia, eastern Finland, after which they identified and counted the approximately 2,000 annual varves in the cores and measured their individual thicknesses and mineral and organic matter contents. These climate-related data were compared with residual Δ^{14}C data derived from tree rings, which serve as a proxy for solar activity (Figure 3.3.6.1).

According to Haltia-Hovi *et al*., their "comparison of varve parameters (varve thickness, mineral and organic matter accumulation) and the activity of the Sun, as reflected in residual Δ^{14}C [data] appears to coincide remarkably well in Lake Lehmilampi during the last 2000 years, suggesting

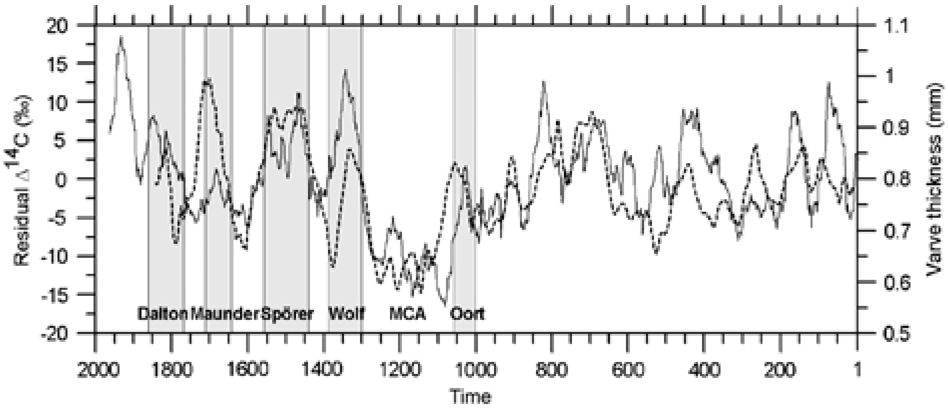

Figure 3.3.6.1. Residual Δ^{14}C data (dashed line) and varve thickness (smooth line) vs. time, specifically highlighting the Oort, Wolf, Sporer, Maunder and Dalton solar activity minima, as well as the "Medieval Climate Anomaly (also referred to as Medieval Warm Period)," during the contemporaneous "solar activity maxima in the Middle Ages." Reprinted with permission from Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.

solar forcing of the climate," as depicted in the figure below for the case of varve thickness. In addition, the low deposition rate of mineral matter in Lake Lehmilampi in AD 1060–1280 "possibly implies mild winters with a short ice cover period during that time with minor snow accumulation interrupted by thawing periods." They say the low accumulation of organic matter during this period "suggests a long open water season and a high decomposition rate of organic matter." Consequently, since the AD 1060–1280 period shows the lowest levels of both mineral and organic matter content, and since "the thinnest varves of the last 2000 years were deposited during [the] solar activity maxima in the Middle Ages," it is difficult not to conclude that period was likely the warmest of the past two millennia in that part of the world.

Helama *et al*. (2010) examined the Sun-climate relationship in unprecedented detail over the mid- to late-Holocene, beginning a new exploration of Sun-climate co-variations on bimillennial and millennial timescales. They produced a well-dated and annually resolved tree-ring proxy temperature reconstruction from 5500 BCE to 2004 CE representative of the high Arctic region of Northern Lapland, Finland, and Norway (68–70°N, 20–30°E), after which they employed the reconstructed sunspot series for the past 11,000 years developed by Solanki and colleagues in 2004 as a proxy for their solar activity index. Although Helama *et al.* confirmed temperature oscillations on centennial and bicentennial timescales, they focused their study on bimillennial and millennial timescale variations.

Figure 3.3.6.2 shows the band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series are very well correlated if one introduces a time lag of about 70 years. The statistical correlations between the two Sun-climate variables change with time but become more significant during the past 2,000 years with $r = 0.796$ and $p = 0.0066$. The authors were unable to demonstrate similar positive or significant correlations for the Sun-climate variables for bimillennial (band-pass filtering of 1,150 to 3,000 years) scale variations for the past two thousand years (late Holocene), but stronger correlations (with $r = 0.877$ and $p = 0.0121$) were shown to exist between sunspot activity and temperatures at high-latitude Lapland for the Mid Holocene interval at the bimillennial timescale (not shown).

Helama *et al*. suggest the statistical correlations for the Sun and temperature series on millennial timescales depicted in Figure 3.3.6.2 are probably realistic and physically meaningful, especially accounting for a time lag of 60 to 80 years. They posit solar activity may have driven the advection of cold surface waters southward and eastward in the subpolar North Atlantic, and that cold water perturbation may ultimately influence the production of the North Atlantic deep water down to a depth of 2,000 meters. Actions within the high Arctic would take time to propagate further south to affect the formation and working of the North Atlantic Meridional Overturning Circulation; such time lags, although in a shorter range of five to 30 years, have been shown by Eichler *et al*. (2010) and Soon (2009) to be necessary for a physical connection between changes in the Sun and climatic conditions around Europe and North and tropical Atlantic regions.

Helama *et al*. also briefly discuss plausible Sun-climate mechanisms through the atmosphere, invoking changing tropospheric-stratospheric temperature gradients. They ultimately conclude a pathway and mechanism involving the ocean for both memory and redistribution of heat are probably needed to explain what they observed.

Importantly for projections of future climate, Helama *et al*. point out "the near-centennial delay in climate in responding to sunspots indicates that the Sun's influence on climate arising from the current episode of high sunspot numbers [which are the most pronounced of the entire record] may not yet have manifested itself fully in climate trends." They note, "if neglected in climate models, this lag could cause an underestimation of twenty-first-century warming trends."

Hanna *et al*. (2004) analyzed several climatic variables over the past century to determine whether there is "evidence of recent climatic changes" in Iceland. For the period 1923–2002, they found no trend in either annual or monthly sunshine data. Similar results were reported for annual and monthly pressure data, which exhibited semi-decadal oscillations throughout the 1820–2002 period but no significant upward or downward trend. Precipitation, by contrast, appears to have increased slightly, although the authors question the veracity of the trend, citing a number of biases that may have corrupted the database.

With respect to temperature, however, the authors report all stations at the locations they examined for this variable experienced a net warming since the mid-1800s. The warming was not linear over the entire period. Temperatures rose from their coldest

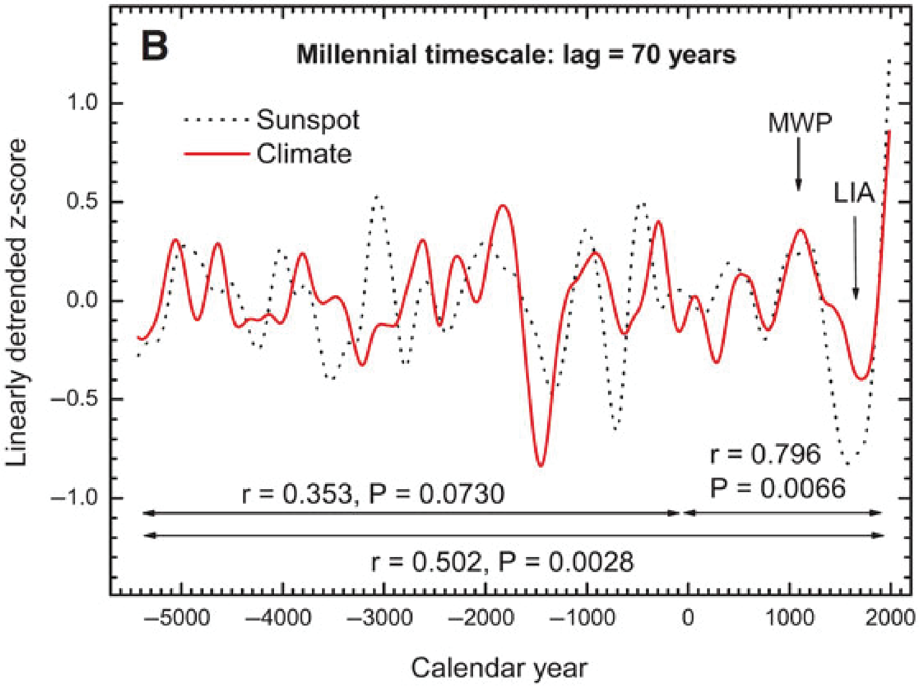

Figure 3.3.6.2. Band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series lagged by 70 years. Reprinted with permission from Helama, S., Fauria, M.M., Mielikainen, K., Timonen, M., and Eronen, M. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988..

levels in the mid-1800s to their warmest levels in the 1930s, whereupon they remained fairly constant for approximately three decades. Then came a period of rapid cooling, which ultimately gave way to the warming of the 1980s and 1990s. The warming of the past two decades has not resulted in temperatures rising above those observed in the 1930s; the authors state emphatically that "the 1990s was definitely not the warmest decade of the 20th century in Iceland, in contrast to the Northern Hemisphere land average." A linear trend fit to the post-1930 data would indicate an overall temperature decrease since that time.

Hanna *et al.* find a significant correlation between 11-year running temperature means and sunspot numbers, plus the presence of a 12-year peak in their spectral analysis of the pressure data, which they say is "suggestive of solar activity."

Other studies from northern Europe have found similar solar-climate linkages. Temperatures of a Swiss Alpine lake over the past 10,000 years were found to vary with changes in solar activity (Niemann *et al*., 2012). Millennial-scale solar cycles also were found to be responsible for Alpine glacier movement (Nussbaumer *et al*., 2011). Similar cycles also were found in Finnish Lapland. Interestingly, each successive warm phase over the past 2,500 years has been colder than the previous (Esper *et al*., 2012), marking a long-term cooling hardly compatible with the looming climate catastrophe alleged by the IPCC.

Norwegian studies have revealed a significant part of the warming there has been caused by the Sun (Solheim *et al*., 2011; 2012; Humlum *et al*., 2011; Vorren *et al*., 2012). Climate and solar activity also are tightly coupled in Sweden (Kokfelt and Muscheler, 2012). In Finland, evidence of solar cycles has been discovered in tree rings (Ogurtsov *et al*., 2011). Baltic Sea ice extent is known to be influenced by solar activity (Leal-Silva and Velasco Herrera, 2012), as is the ice on the Rhine River in Central Europe (Sirocko *et al*., 2012). A massive cold period in Central Europe 2,800 years ago appears to have been triggered by a weak Sun (Martin-Puertas *et al*., 2012). The North Atlantic deep water formation was found to be modulated by the Sun (Morley *et al*., 2011). The famous rains in Northern Ireland are affected by changes in solar activity (Swindles *et al*., 2012). Winds in Portugal blew particularly strong when the Sun was weak (Costas *et al*., 2012). Solar activity fluctuations and the North Atlantic Oscillation (NAO) have contributed to Italy's climate of the past 10,000 years (Scholz *et al*., 2012). A solar influence also could be detected in Italian salt marshes (Di Ritam 2013).

Noting "solar activity during the current sunspot minimum has fallen to levels unknown since the start of the 20th century" and "the Maunder minimum (about 1650–1700) was a prolonged episode of low solar activity which coincided with more severe winters in the United Kingdom and continental Europe," Lockwood *et al*. (2010) were "motivated by recent relatively cold winters in the UK" to investigate the possible connection between these severe winters and low solar activity. They identified "regionally anomalous cold winters by detrending the Central England temperature record using reconstructions of the northern hemisphere mean temperature" and discovered "cold winter excursions from the hemispheric trend" do indeed "occur more commonly in the UK during low solar activity, consistent with the solar influence on the occurrence of persistent blocking events in the eastern Atlantic." They state "colder UK winters (relative to the longer-term trend) can therefore be associated with lower open solar flux (and hence with lower solar irradiance and higher cosmic ray flux)."

Lockwood *et al.* are quick to note "this is a regional and seasonal effect relating to European winters and not a global effect." But they also note "average solar activity has declined rapidly since 1985 and cosmogenic isotopes suggest an 8% chance of a return to Maunder minimum conditions within the next 50 years (Lockwood, 2010)," suggesting "despite hemispheric warming, the UK and Europe could experience more cold winters than during recent decades."

Mangini *et al*. (2005) developed a highly resolved 2,000-year δ^{18}O proxy record of temperature obtained from a stalagmite recovered from Spannagel Cave in the Central Alps of Austria. They found the lowest temperatures of the past two millennia occurred during the Little Ice Age (AD 1400–1850), while the highest temperatures were found in the Medieval Warm Period (MWP: AD 800–1300). They report the highest temperatures of the MWP were "slightly higher than those of the top section of the stalagmite (1950 AD) and higher than the present-day temperature." At three different points during the MWP, their data indicate temperature spikes in excess of 1°C above present (1995–1998) temperatures.

Mangini *et al.* also report their temperature reconstruction compares well with reconstructions developed from Greenland ice cores (Muller and Gordon, 2000), Bermuda Rise ocean-bottom sediments (Keigwin, 1996), and glacier tongue advances and retreats in the Alps (Holzhauser, 1997; Wanner *et al*., 2000), as well as with the Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005). Considered together, they say, these several data sets "indicate that the MWP was a climatically distinct period in the Northern Hemisphere," emphasizing "this conclusion is in strong contradiction to the temperature reconstruction by the IPCC, which only sees the last 100 years as a period of increased temperature during the last 2000 years."

Mangini *et al*. also found "a high correlation between δ^{18}O and δ^{14}C, that reflects the amount of radiocarbon in the upper atmosphere," and they note this correlation "suggests that solar variability was a major driver of climate in Central Europe during the past 2 millennia." They report "the maxima of δ^{18}O coincide with solar minima (Dalton, Maunder, Sporer, Wolf, as well as with minima at around AD 700, 500 and 300)" and "the coldest period between 1688 and 1698 coincided with the Maunder Minimum." Also, in a linear-model analysis of the percent of variance of their full temperature reconstruction that is individually explained by solar and CO_2 forcing, they found the impact of the Sun was fully 279 times greater than that of the air's CO_2 concentration, noting "the flat evolution of CO_2 during the first 19 centuries yields almost vanishing correlation coefficients with the temperature reconstructions."

Two years later, Mangini *et al*. (2007) updated the 2005 study with additional data and compared it with the Hematite-Stained-Grain (HSG) history of ice-rafted debris in North Atlantic Ocean sediments developed by Bond *et al*. (2001). They found an undeniably good correspondence between the peaks and valleys of their δ^{18}O curve and the HSG curve. Recall from our previous discussion of Bond *et al*.'s work this conclusion: "Over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

Other researchers have found similar periodicities in their climate proxies. Turner *et al*. (2008), for example, found an ~1,500 year cycle in a climate history reconstructed from sediment cores extracted from two crater lake basins in central Turkey, which they indicate "may be linked with large-scale climate forcing" such as that found in the North Atlantic by Bond *et al*. (1997, 2001). In addition, McDermott *et al*. (2001) found evidence of millennial-scale climate cycles in a $\delta^{18}O$ record from a stalagmite in southwestern Ireland, as did Sbaffi *et al*. (2004) from two deep-sea sediment cores recovered from the Tyrrhenian Sea, which corresponded well with the North Atlantic solar-driven cycles of Bond *et al*. (1997).

In the Mediterranean Sea, Cini Castagnoli *et al*. (2002) searched for solar-induced variations in the $\delta^{13}C$ record of the foraminifera *Globigerinoides rubber* obtained from a sea core located in the Gallipoli terrace of the Gulf of Taranto (39°45'53"N, 17°53'33"E, depth of 178 m) over the past 1,400 years. Starting at the beginning of the 1,400-year record, the $\delta^{13}C$ values increased from about 0.4 per mil around 600 A.D. to a value of 0.8 per mil by 900 A.D. Thereafter, the $\delta^{13}C$ record remained relatively constant until about 1800, when it rose another 0.2 per mil to its present-day value of around 1.0 per mil.

Using statistical procedures, the authors identified three important cyclical components in their record, with periods of approximately 11.3, 100, and 200 years. Comparison of both the raw $\delta^{13}C$ and component data with the historical aurorae and sunspot time series, respectively, revealed the records are "associable in phase" and "disclose a statistically significant imprint of the solar activity in a climate record." Three years later, Cini Castagnoli *et al*. (2005) extended the $\delta^{13}C$ temperature proxy from the Gulf of Taranto an additional 600 years, reporting an overall phase agreement between the climate reconstruction and variations in the sunspot number series that "favors the hypothesis that the [multi-decadal] oscillation revealed in $\delta^{13}C$ is connected to the solar activity."

Chen *et al*. (2011) developed a high temporal resolution (four-year) sea surface temperature (SST) history based on a dinoflagelate cyst record obtained from a well-dated sediment core retrieved from a site in the Gulf of Taranto located at the distal end of the Po River discharge plume (39°50.07'N, 17°48.05'E). Their analysis revealed an era of "high stable temperatures between 60 BC and 90 AD followed by a decreasing trend between 90 AD and 200 AD." And "consistent to earlier findings for the region," they state "local air temperature during the Roman Period might have been warmer than that of the 20th century." The authors write, "the observation of strong 11 years cyclicity in our records together with a strong visual correlation of our temperature and river discharge records with the global variation in $\Delta^{14}C$ anomalies suggest that solar activity might have been an important climate forcing factor during this time."

Desprat *et al*. (2003) conducted a high-resolution pollen analysis of a sediment core retrieved from the central axis of the Ria de Vigo in the south of Galicia (42°14.07'N, 8°47.37'W) to study the climatic variability of the last three millennia in northwest Iberia. According to the authors, over the past 3,000 years there was "an alternation of three relatively cold periods with three relatively warm episodes." In order of their occurrence, those periods were described by the authors as the "first cold phase of the Subatlantic period (975–250 BC)," "followed by the Roman Warm Period (250 BC–450 AD)," followed by "a successive cold period (450–950 AD), the Dark Ages," which "was terminated by the onset of the Medieval Warm Period (950–1400 AD)," followed by "the Little Ice Age (1400–1850 AD), including the Maunder Minimum (at around 1700 AD)," which "was succeeded by the recent warming (1850 AD to the present)." Based on this "millennial-scale climatic cyclicity over the last 3000 years," which parallels "global climatic changes recorded in North Atlantic marine records (Bond *et al*., 1997; Bianchi and McCave, 1999; Chapman and Shackelton, 2000)," Desprat *et al*. conclude "solar radiative budget and oceanic circulation seem to be the main mechanisms forcing this cyclicity in NW Iberia."

Morellon *et al*. (2011) note, "in the context of present-day global warming, there is increased interest in documenting climate variability during the last millennium" because "it is crucial to reconstruct pre-industrial conditions to discriminate anthropogenic components (i.e., greenhouse gases, land-use changes) from natural forcings (i.e., solar variability, volcanic emissions)." They conducted a multi-proxy study of several short sediment cores recovered from Lake Estanya (42°02'N, 0°32'E) in the Pre-Pyrenean Ranges of northeast Spain, providing "a detailed record of the complex environmental, hydrological and anthropogenic interactions occurring in the area since medieval times." They report "the integration of sedimentary facies, elemental and isotopic geochemistry, and biological proxies (diatoms, chironomids and pollen), together with a robust chronological control, provided by AMS radiocarbon dating and ^{210}Pb and ^{137}Cs radiometric techniques, enabled precise reconstruction of the main phases of environmental change, associated with the Medieval

Warm Period (MWP), the Little Ice Age (LIA) and the industrial era."

The 13 researchers identified the MWP as occurring in their record from AD 1150 to 1300, noting their pollen data reflect "warmer and drier conditions" in harmony with the higher temperatures of the Iberian Peninsula over the same time period documented by Martinez-Cortizas *et al*. (1999), the higher temperatures of the Western Mediterranean region found by Taricco *et al*. (2008), and the global reconstructions of Crowley and Lowery (2000) and Osborn and Briffa (2006), which "clearly document warmer conditions from the twelfth to fourteenth centuries." Morellon *et al*. conclude this warmth is "likely related to increased solar irradiance (Bard *et al*., 2000), persistent La Niña-like tropical Pacific conditions, a warm phase of the Atlantic Multidecadal Oscillation, and a more frequent positive phase of the North Atlantic Oscillation (Seager *et al*., 2007)."

Morellon *et al*. also note the occurrence of the LIA, which they recognize as occurring from AD 1300 to 1850. On the Iberian Peninsula, they report, "lower temperatures (Martinez-Cortizas *et al*., 1999) characterize this period," which "coincided with colder North Atlantic (Bond *et al*., 2001) and Mediterranean sea surface temperatures (Taricco *et al*., 2008) and a phase of mountain glacier advance (Wanner *et al*., 2008)." Following the LIA they identify the transition period of AD 1850–2004 that takes the region into the Current Warm Period.

In discussing these periods, the authors say "a comparison of the main hydrological transitions during the last 800 years in Lake Estanya and solar irradiance (Bard *et al*., 2000) reveals that lower lake levels dominated during periods of enhanced solar activity (MWP and post-1850 AD) and higher lake levels during periods of diminished solar activity (LIA)." Within the LIA they note periods of higher lake levels or evidence of increased water balance occurred during the solar minima of Wolf (AD 1282–1342), Sporer (AD 1460–1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1820).

Paleoclimatic studies from Europe provide more evidence for the global reality of solar-induced temperature oscillations pervading both glacial and interglacial periods, and these oscillations are looking more and more likely as the primary forcing agent responsible for driving temperature change during the Current Warm Period. The concurrent historical increase in the air's CO_2 content, on the other hand, has likely exerted only minimal influence.

References

Ammann, C.M., Joos, F., Schimel, D.S., Otto-Bliesner, B.L., and Tomas, R.A. 2007. Solar influence on climate during the past millennium: Results from transient simulations with the NCAR Climate System Model. *Proceedings of the National Academy of Sciences USA* **104**: 3713–3718.

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus* **52B**: 985–992.

Berstad, I.M., Sejrup, H.P., Klitgaard-Kristensen, D., and Haflidason, H. 2003. Variability in temperature and geometry of the Norwegian Current over the past 600 yr; stable isotope and grain size evidence from the Norwegian margin. *Journal of Quaternary Science* **18**: 591–602.

Bianchi, G.G. and McCave, I.N. 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* **397**: 515–517.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, L., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. *Science* **278**: 1257–1266.

Chapman, M.R. and Shackelton, N.L. 2000. Evidence of 550-year and 1000-year cyclicities in North Atlantic circulation patterns during the Holocene. *The Holocene* **10**: 287–291.

Chen, L., Zonneveld, K.A.F., and Versteegh, G.J.M. 2011. Short term climate variability during the "Roman Classical Period" in the eastern Mediterranean. *Quaternary Science Reviews* **30**: 3880–3891.

Cini Castagnoli, G.C., Bonino, G., Taricco, C., and Bernasconi, S.M. 2002. Solar radiation variability in the last 1400 years recorded in the carbon isotope ratio of a Mediterranean sea core. *Advances in Space Research* **29**: 1989–1994.

Cini Castagnoli, G., Taricco, C., and Alessio, S. 2005. Isotopic record in a marine shallow-water core: Imprint of solar centennial cycles in the past 2 millennia. *Advances in Space Research* **35**: 504–508.

Costas, S., Jerez, S., Trigo, R. M., Goble, R., and Rebêlo, L. 2012. Sand invasion along the Portuguese coast forced by westerly shifts during cold climate events. *Quaternary Science Reviews* **42**: 15–28.

Crowley, T.J. 2000. Causes of climate change over the past 1000 years. *Science* **289**: 270–277.

Crowley, T.J. and Lowery, T.S. 2000. How warm was the Medieval Warm Period? *Ambio* **29**: 51–54.

Denton, G.H. and Karlén, W. 1973. Holocene climate variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.

Desprat, S., Goñi, M.F.S., and Loutre, M.-F. 2003. Revealing climatic variability of the last three millennia in northwestern Iberia using pollen influx data. *Earth and Planetary Science Letters* **213**: 63–78.

Di Rita, F. 2013. A possible solar pacemaker for Holocene fluctuations of a salt-marsh in southern Italy. *Quaternary International* **288**: 239–248.

Eichler, A., Olivier, S., Henderson, S.K., Laube, A., Beer, J., Papina, T., and Gaggler, H.W. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988.

Esper, J., Frank, D. C., Timonen, M., Zorita, E., Wilson, R. J. S. , Luterbacher, J., Holzkämpe, S., Fischer, N., Wagner, S., Nievergelt, D., Verstege, A., and Büntgen, U. 2012. Orbital forcing of tree-ring data. *Nature Climate Change* **2**: 862–866.

Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.

Hanna, H., Jónsson, T., and Box, J.E. 2004. An analysis of Icelandic climate since the nineteenth century. *International Journal of Climatology* **24**: 1193–1210.

Helama, S., Fauria, M.M., Mielikainen, K., Timonen, M., and Eronen, M. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988.

Holzhauser, H. 1997. Fluctuations of the Grosser Aletsch Glacier and the Gorner Glacier during the last 3200 years: new results. In: Frenzel, B. (Ed.) *Glacier Fluctuations During the Holocene*. Fischer, Stuttgart, Germany, pp. 35–58.

Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* **15**: 789–801.

Hormes, A., Beer, J., and Schluchter, C. 2006. A geochronological approach to understanding the role of solar activity on Holocene glacier length variability in the Swiss Alps. *Geografiska Annaler Series A* **88**: 281–294.

Humlum, O., Solheim, J.-E., and Stordahl, K. 2011. Identifying natural contributions to late Holocene climate change. *Global and Planetary Change* **79**: 145–156.

Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1503–1508.

Kilian, M.R., van der Plicht, J., and van Geel, B. 1995. Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* **14**: 959–966.

Kokfelt, U. and Muscheler, R. 2012. Solar forcing of climate during the last millennium recorded in lake sediments from northern Sweden. *The Holocene* **23**: 447–452.

Leal-Silva, M.C. and Velasco Herrera, V. M. 2012. Solar forcing on the ice winter severity index in the western Baltic region. *Journal of Atmospheric and Solar-Terrestrial Physics* **89**: 98–109.

Lockwood, M. 2010. Solar change and climate: an update in the light of the current exceptional solar minimum. *Proceedings of the Royal Society A* **466**: 303–329.

Lockwood, M., Harrison, R.G., Woolings, T., and Solanki, S.K. 2010. Are cold winters in Europe associated with low solar activity? *Environmental Research Letters* **5**: 10.1088/1748-9326/5/2/024001.

Magny, M. 1993. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* **40**: 1–9.

Mangini, A., Spotl, C., and Verdes, P. 2005. Reconstruction of temperature in the Central Alps during the past 2000 yr from a δ^{18}O stalagmite record. *Earth and Planetary Science Letters* **235**: 741–751.

Mangini, A., Verdes, P., Spotl, C., Scholz, D., Vollweiler, N., and Kromer, B. 2007. Persistent influence of the North Atlantic hydrography on central European winter temperature during the last 9000 years. *Geophysical Research Letters* **34**: 10.1029/2006GL028600.

Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G., and van Geel, B. 2012. Regional atmospheric circulation shifts induced by a grand solar minimum. *Nature Geoscience* doi:10.1038/ngeo1460.

Martinez-Cortizas, A., Pontevedra-Pombal, X., Garcia-Rodeja, E., Novoa-Muñoz, J.C., and Shotyk, W. 1999. Mercury in a Spanish peat bog: Archive of climate change and atmospheric metal deposition. *Science* **284**: 939–942.

Mauquoy, D., Engelkes, T., Groot, M.H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J., and van Geel, B. 2002b. High resolution records of late Holocene climate change and carbon accumulation in two north-west

European ombrotrophic peat bogs. *Palaeogeography, Palaeoclimatology, Palaeoecology* **186**: 275–310.

Mauquoy, D., van Geel, B., Blaauw, M., Speranza, A., and van der Plicht, J. 2004. Changes in solar activity and Holocene climatic shifts derived from ^{14}C wiggle-match dated peat deposits. *The Holocene* **14**: 45–52.

Mauquoy, D., van Geel, B., Blaauw, M., and van der Plicht, J. 2002a. Evidence from North-West European bogs shows 'Little Ice Age' climatic changes driven by changes in solar activity. *The Holocene* **12**: 1–6.

McDermott, F., Mattey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem δ^{18}O record from SW Ireland. *Science* **294**: 1328–1331.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlén, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Morellon, M., Valero-Garces, B., Gonzalez-Samperiz, P., Vegas-Vilarrubia, T., Rubio, E., Rieradevall, M., Delgado-Huertas, A., Mata, P., Romero, O., Engstrom, D.R., Lopez-Vicente, M., Navas, A., and Soto, J. 2011. Climate changes and human activities recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age. *Journal of Paleolimnology* **46**: 423–452.

Morley, A., Schulz, M., Rosenthal, Y., Mulitza, S., Paul, A., and Rühlemann, C. 2011. Solar modulation of North Atlantic central Water formation at multidecadal timescales during the late Holocene. *Earth and Planetary Science Letters* **308**: 161–171.

Muller, R.A. and Gordon, J.M. 2000. *Ice Ages and Astronomical Causes*. Springer-Verlag, Berlin, Germany.

Niemann, H., Stadnitskaia, A., Wirth, S.B., Gilli, A., Anselmetti, F.S., Sinninghe Damsté, J.S., Schouten, S., Hopmans, E.C., and Lehmann, M.F. 2012. Bacterial GDGTs in Holocene sediments and catchment soils of a high-alpine lake: application of the MBT/CBT-paleothermometer. *Climate of the Past* **8**: 889–906.

Nussbaumer, S.U., Steinhilber, F., Trachsel, M., Breitenmoser, P., Beer, J., Blass, A., Grosjean, M., Hafner, A., Holzhauser, H., Wanner, H., and Zumbühl, H.J. 2011. Alpine climate during the Holocene: a comparison between records of glaciers, lake sediments and solar activity. *Journal of Quaternary Science* **26**: 703–713.

Ogurtsov, M., Sonninen, E. Hilasvuori, E., Koudriavtsev, I., Dergachev, V., and Jungner, H. 2011. Variations in tree ring stable isotope records from northern Finland and their possible connection to solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 383–387.

Osborn, T.J. and Briffa, K.R. 2006. The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science* **311**: 841–844.

Sbaffi, L., Wezel, F.C., Curzi, G., and Zoppi, U. 2004. Millennial- to centennial-scale palaeoclimatic variations during Termination I and the Holocene in the central Mediterranean Sea. *Global and Planetary Change* **40**: 201–217.

Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., and Mangini, A. 2012. Holocene climate variability in north-eastern Italy: potential influence of the NAO and solar activity recorded by speleothem data. *Climate of the Past* **8**: 1367–1383.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.

Sejrup, H.P., Lehman, S.J., Haflidason, H., Noone, D., Muscheler, R., Berstad, I.M., and Andrews, J.T. 2010. Response of Norwegian Sea temperature to solar forcing since 1000 A.D. *Journal of Geophysical Research* **115**: 10.1029/2010JC006264.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., and Waple, A. 2001. Solar forcing of regional climate change during the maunder minimum. *Science* **294**: 2149–2152.

Sirocko, F., Brunck, H., and Pfahl, S. 2012. Solar influence on winter severity in central Europe. *Geophysical Research Letters* **39**: L16704, doi:10.1029/2012GL052412.

Solheim, J.-E., Stordahl, K., and Humlum, O. 2011. Solar Activity and Svalbard Temperatures. *Advances in Meteorology* Article ID 543146, doi:10.1155/2011/543146.

Solheim, J.-E., Stordahl, K., and Humlum, O. 2012. The long sunspot cycle 23 predicts a significant temperature decrease in cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 267–284.

Soon, W.W.-H. 2009. Solar Arctic-mediated climate variation on multidecadal to centennial timescales: Empirical evidence, mechanistic explanation, and testable consequences. *Physical Geography* **30**: 144–184.

Speranza, A. 2000. Solar and Anthropogenic Forcing of Late-Holocene Vegetation Changes in the Czech Giant Mountains. PhD thesis. University of Amsterdam, Amsterdam, The Netherlands.

Speranza, A.O.M., van der Plicht, J., and van Geel, B. 2000. Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching. *Quaternary Science Reviews* **19**: 1589–1604.

Stuiver, M. and Polach, H.A. 1977. Discussion: reporting ^{14}C data. *Radiocarbon* **19**: 355–363.

Swindles, G.T., Patterson, R.T., Roe, H.M., and Galloway, J.M. 2012. Evaluating periodicities in peat-based climate proxy records. *Quaternary Science Reviews* **41**: 94–103.

Taricco, C., Ghil, M., and Vivaldo, G. 2008. Two millennia of climate variability in the Central Mediterranean. *Climate of the Past Discussions* **4**: 1089–1113.

Tinner, W., Lotter, A.F., Ammann, B., Condera, M., Hubschmied, P., van Leeuwan, J.F.N., and Wehrli, M. 2003. Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to AD 800. *Quaternary Science Reviews* **22**: 1447–1460.

Tung, K.K. and Camp, C.D. 2008. Solar cycle warming at the Earth's surface in NCEP and ERA-40 data: A linear discriminant analysis. *Journal of Geophysical Research* **113**: 10.1029/2007JD009164.

Turner, R., Roberts, N., and Jones, M.D. 2008. Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. *Global and Planetary Change* **63**: 317–324.

Usoskin, I.G., Solanki, S.K., Schussler, M., Mursula, K., and Alanko, K. 2003. Millennium-scale Sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s. *Physical Review Letters* **91**: 10.1103/ PhysRevLett.91.211101.

van Geel, B., Buurman, J., and Waterbolk, H.T. 1996. Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science* **11**: 451–460.

van Geel, B., Heusser, C.J., Renssen, H., and Schuurmans, C.J.E. 2000. Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis. *The Holocene* **10**: 659–664.

van Geel, B. and Mook, W.G. 1989. High resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations. *Radiocarbon* **31**: 151–155.

van Geel, B., Raspopov, O.M., Renssen, H., van der Plicht, J., Dergachev, V.A., and Meijer, H.A.J. 1999. The role of solar forcing upon climate change. *Quaternary Science Reviews* **18**: 331–338.

van Geel, B., van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M., Renssen, H., Reynaud-Farrera, I., and Waterbolk, H.T. 1998. The sharp rise of delta ^{14}C c. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* **40**: 535–550.

Vorren, K.-D., Jensen, C.E., and Nilssen, E. 2012. Climate changes during the last c. 7500 years as recorded by the degree of peat humification in the Lofoten region, Norway. *Boreas* **41**: 13–30.

Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid- to late Holocene climate change: an overview. *Quaternary Science Reviews* **27**: 1791–1828.

Wanner, H., Dimitrios, G., Luterbacher, J., Rickli, R., Salvisberg, E., and Schmutz, C. 2000. *Klimawandel im Schweizer Alpenraum*. VDF Hochschulverlag, Zurich, Switzerland.

Woods, T.N. and Lean, J. 2007. Anticipating the next decade of sun-earth system variations. *EOS, Transactions, American Geophysical Union* **88**: 457–458.

3.3.7 Other Geographical Regions

Van Geel *et al.* (1999) examined the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. They write, "there is mounting evidence suggesting that the variation in solar activity is a cause for millennial-scale climate change," which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth's orbit about the Sun. They add, "accepting the idea of solar forcing of Holocene and Glacial climatic shifts has major implications for our view of present and future climate," for it implies, as they note, "the climate system is far more sensitive to small variations in solar activity than generally believed" and "it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation."

Tyson *et al.* (2000) obtained a quasi-decadal-resolution record of oxygen and carbon-stable isotope data from a well-dated stalagmite recovered from Cold Air Cave in the Makapansgat Valley, 30 km southwest of Pietersburg, South Africa. They augmented that record with temperature data reconstructed from color variations in banded growth-layer laminations of the stalagmite derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981–1995, which had a correlation of +0.78 that was significant at the 99 percent confidence level.

The authors found both the Little Ice Age (prevailing from about AD 1300 to 1800) and the Medieval Warm Period (prevailing from before AD 1000 to around 1300) to be distinctive features of the climate of the last millennium. Compared with the period 1961–1990, the Little Ice Age, "a widespread event in South Africa specifically and southern Africa generally," was characterized by a mean annual temperature depression of about 1°C at its coolest point. The Medieval Warm Period, by contrast, was as much as 3–4°C warmer at its warmest point. The researchers also note the coolest point of the Little Ice Age corresponded with the Maunder Minimum of sunspot activity and the Medieval Warm Period corresponded with the Medieval Maximum in solar activity.

In a study demonstrating a solar-climate link on shorter decadal to centennial time scales, Domack *et al*. (2001) examined ocean sediment cores obtained from the Palmer Deep on the inner continental shelf of the western Antarctic Peninsula (64° 51.71' S, 64° 12.47' W) to produce a high-resolution proxy temperature history of that area spanning the past 13,000 years. They identified five prominent palaeo-environmental intervals over the past 14,000 years: (1) a "Neoglacial" cool period beginning 3,360 years ago and continuing to the present, (2) a mid-Holocene climatic optimum from 9,070 to 3,360 years ago, (3) a cool period beginning 11,460 years ago and ending at 9,070 years ago, (4) a warm period from 13,180 to 11,460 years ago, and (5) cold glacial conditions prior to 13,180 years ago. Spectral analyses of the data revealed decadal and centennial-scale temperature cycles superimposed upon these broad climatic intervals. Throughout the current Neoglacial period, they report finding "very significant" (above the 99 percent confidence level) peaks, or oscillations, that occurred at intervals of 400, 190, 122, 85, and 70 years, which they suggest are perhaps driven by solar variability.

Dima *et al*. (2005) performed Singular Spectrum Analysis on a Rarotonga coral-based sea surface temperature (SST) reconstruction from the warmer ocean waters off the Cook Islands, South Pacific Ocean in an effort to determine the dominant periods of multidecadal variability in the series over the period 1727–1996. Their work revealed two dominant multidecadal cycles with periods of about 25 and 80 years. These modes of variability were determined to be similar to multidecadal modes found in the global SST field of Kaplan *et al*. (1998) for the period 1856–1996. The ~25-year cycle was found to be associated with the well-known Pacific Decadal Oscillation, whereas the ~80-year cycle was determined to be "almost identical" to a pattern of solar forcing found by Lohmann *et al*. (2004), which, according to Dima *et al*., "points to a possible solar origin" of this mode of SST variability.

Bard and Frank (2006) reviewed what is known and unknown about solar variability and its effects on Earth's climate over the past few decades, the past few centuries, the entire Holocene, and orbital timescales. With respect to the three suborbital time scales, Bard and Frank conclude, "it appears that solar fluctuations were involved in causing widespread but limited climatic changes, such as the Little Ice Age (AD 1500–1800) that followed the Medieval Warm Period (AD 900–1400)." They write, "the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: The so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500–1800)."

Bard and Frank note, "Bond *et al*. (1997, 2001) followed by Hu *et al*. (2003) proposed that variations of solar activity are responsible for quasi-periodic climatic and oceanographic fluctuations that follow cycles of about one to two millennia." They write, "the succession from the Medieval Warm Period to the Little Ice Age would thus represent the last [such] cycle," leading them to conclude "our present climate is in an ascending phase on its way to attaining a new warm optimum" resulting from some form of solar variability. In addition, they note, "a recent modeling study suggests that an apparent 1500-year cycle could arise from the superimposed influence of the 90 and 210 year solar cycles on the climate system, which is characterized by both nonlinear dynamics and long time scale memory effects (Braun *et al*. 2005)."

The studies discussed in this and previous subsections examining solar influence on temperature demonstrate the warming of Earth since the termination of the Little Ice Age is not unusual or different from other climate changes of the past millennium, when atmospheric CO_2 concentrations were stable, lower than at present, and not responsible for the observed variations in temperature. This further suggests the warming of the past century had little to do with the contemporaneous historical increase in the air's CO_2 content.

References

Bard, E. and Frank, M. 2006. Climate change and solar variability: What's new under the Sun? *Earth and Planetary Science Letters* **248**: 1–14.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climate. *Science* **278**: 1257–1266.

Braun, H., Christl, M., Rahmstorf, S., Ganopolski, A., Mangini, A., Kubatzki, C., Roth, K., and Kromer, B. 2005. Possible solar origin of the 1470-year glacial climate cycle demonstrated in a coupled model. *Nature* **438**: 208–211.

Dima, M., Felis, T., Lohmann, G., and Rimbu, N. 2005. Distinct modes of bidecadal and multidecadal variability in a climate reconstruction of the last centuries from a South Pacific coral. *Climate Dynamics* **25**: 329–336.

Domack, E., Leventer, A., Dunbar, R., Taylor, F., Brachfeld, S., Sjunneskog, C., and ODP Leg 178 Scientific Party. 2001. Chronology of the Palmer Deep site, Antarctic Peninsula: A Holocene palaeoenvironmental reference for the circum-Antarctic. *The Holocene* **11**: 1–9.

Hu, F.S., Kaufman, D., Yoneji, S., Nelson, D., Shemesh, A., Huang, Y., Tian, J., Bond, G., Clegg, B., and Brown, T. 2003. Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic. *Science* **301**: 1890–1893.

Kaplan, A., Cane, M.A., Kushnir, Y., Clement, A.C., Blumenthal, M.B., and Rajagopalan, B. 1998. Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research* **103**: 18,567–18,589.

Lohmann, G., Rimbu, N., and Dima, M. 2004. Climate signature of solar irradiance variations: analysis of long-term instrumental, historical, and proxy data. *International Journal of Climatology* **24**: 1045–1056.

Tyson, P.D., Karlén, W., Holmgren, K., and Heiss, G.A. 2000. The Little Ice Age and medieval warming in South Africa. *South African Journal of Science* **96**: 121–126.

Van Geel, B., Raspopov, O.M., Renssen, H., van der Plicht, J., Dergachev, V.A., and Meijer, H.A.J. 1999. The role of solar forcing upon climate change. *Quaternary Science Reviews* **18**: 331–338.

3.4 Precipitation

Many researchers have examined historical proxy temperature changes over the past millennia and beyond in an attempt to quantify the magnitude, frequency, and causes of natural climate variability. However, temperature is not always the best measure of climate, and it is certainly not the only measure. Some studies, for example, have examined the millennial range and rate of change of hydrologic and atmospheric circulation; changes in these parameters are important because they are involved in more than half of Earth's poleward transfer of heat (Peixoto and Oort, 1992).

In one such study, Maasch *et al.* (2005) examined changes in eight well-dated high-resolution climate-related records over the past two millennia: K^+ concentrations from the GISP2 ice core in Greenland, Na^+ concentrations from the Siple Dome ice core in Antarctica, percent Ti from an ocean sediment core in the Cariaco basin, Fe intensity from a marine core near the coast of mid-latitude Chile, oxygen isotope fractions from Punta Laguna near the Yucatan, carbon isotope data from a speleothem in Makapansgat, South Africa, percent of shallow water diatoms from Lake Victoria, and lake levels from Lake Naivasha in equatorial Africa. The eight data sets were compared with a history of atmospheric $\Delta^{14}C$, a proxy for solar variability obtained from tree rings, to ascertain what, if any, solar influence operated on these parameters.

Comparison of the $\Delta^{14}C$ solar proxy data with the eight climate-related data sets revealed over the past 2,000 years there has been a "strong association between solar variability and globally distributed climate change." This "remarkable coherence" among the data sets was particularly noticeable in the Medieval Warm Period to Little Ice Age transition, as well as throughout the Little Ice Age.

In this section we review studies that show past trends in precipitation are likely explained better by solar variability than by the IPCC's preferred explanation, rising atmospheric CO_2 concentrations.

References

Maasch, K.A., Mayewski, P.A., Rohling, E.J., Stager, J.C., Karlén, W., Meeker, L.D., and Meyerson, E.A. 2005. A 2000-year context for modern climate change. *Geografiska Annaler* **87** A: 7–15.

Peixoto, J.P. and Oort, A.H. 1992. *Physics of Climate*. American Institute of Physics, New York.

3.4.1 North America

Kristjansson *et al.* (2002) examined the relationship between the Sun and low-level clouds, which are correlated with precipitation. They note solar irradiance "varies by about 0.1% over the 11-year solar cycle, which would appear to be too small to have an impact on climate." Nevertheless, they report "persistent claims have been made of 11-year signals in various meteorological time series, e.g., sea surface temperature (White *et al*., 1997) and cloudiness over North America (Udelhofen and Cess, 2001)."

Kristjansson *et al*. "re-evaluate[d] the statistical relationship between low cloud cover and solar activity adding 6 years of ISCCP [International Satellite Cloud Climatology Project] data that were recently released." For the period 1983–1999, they compared temporal trends of solar irradiance at the top of the atmosphere with low cloud cover trends derived from satellite-borne instruments that provided two measures of cloud cover: full temporal coverage and daytime-only coverage. They found "solar irradiance correlates well with low cloud cover," with the significance level of the correlation being 98 percent for full temporal coverage and 90 percent for daytime-only coverage. In addition, as would be expected if the variations in cloud cover were driven by variations in solar irradiance, they also report lagged correlations between the two parameters revealed a maximum correlation between solar irradiance and low cloud cover when the former leads the latter by one month for full temporal coverage and by four months for daytime-only coverage.

Kristjansson *et al*. observed "low clouds appear to be significantly inversely correlated with solar irradiance," leading them to suggest a possible physical mechanism that could explain this phenomenon. This mechanism "acts through UV [ultraviolet radiation] in the stratosphere affecting tropospheric planetary waves and therefore the subtropical highs, modulated by an interaction between sea surface temperature [SST] and lower tropospheric static stability," which "relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics." Based on experimentally determined values of factors that enter into this scenario, they obtained a value for the amplitude of the variation in low cloud cover over a solar cycle that "is very close to the observed amplitude."

Other authors have examined lake level fluctuations, which are generally highly dependent on precipitation levels. Cumming *et al*. (2002), for example, studied a sediment core retrieved from Big Lake (51°40'N, 121°27'W) on the Cariboo Plateau of British Columbia, Canada, carefully dating it and deriving estimates of changes in precipitation-sensitive limnological variables (salinity and lake depth) from transfer functions based on modern distributions of diatom assemblages in 219 lakes from western Canada.

On the basis of observed changes in patterns of the floristic composition of diatoms over the past 5,500 years, Cumming *et al*. report "alternating millennial-scale periods of high and low moisture availability were inferred, with abrupt transitions in diatom communities occurring 4960, 3770, 2300 and 1140 cal. yrs. BP." They also find "periods of inferred lower lake depth correspond closely to the timing of worldwide Holocene glacier expansions" and the mean length of "the relatively stable intervals between the abrupt transitions ... is similar to the mean Holocene pacing of IRD [ice rafted debris] events ... in the North Atlantic," described by Bond *et al*. (1997) and attributed to "solar variability amplified through oceanic and atmospheric dynamics," as detailed by Bond *et al*. (2001).

Li *et al*. (2006, 2007) also developed a precipitation proxy from a lake-level record, based on lithologic and mineral magnetic data from the Holocene sediments of White Lake, New Jersey, northeastern USA (41°N, 74.8°W), the characteristics of which they compared with a host of other paleoclimatic reconstructions from this region and beyond.

According to the authors of these two papers (Li *et al*., 2006; 2007), the lake-level history revealed low lake levels at ~1.3, 3.0, 4.4, and 6.1 thousand years before present. Comparison of the results with drift-ice records from the North Atlantic Ocean according to Li *et al*. (2007) "indicates a striking correspondence," as they "correlate well with cold events 1, 2, 3 and 4 of Bond *et al*. (2001)." They also report a comparison of their results with those of other land-based studies suggests "a temporally coherent pattern of climate variations at a quasi-1500-year periodicity at least in the Mid-Atlantic region, if not the entire northeastern USA." In addition, they note "the Mid-Atlantic region was dominated by wet conditions, while most parts of the conterminous USA experienced droughts, when the North Atlantic Ocean was warm."

The three researchers say the dry-cold correlation they found "resembles the modern observed relationship between moisture conditions in eastern North America and the North Atlantic Oscillation (NAO), but operates at millennial timescales, possibly through modulation of atmospheric dynamics by solar forcing," In this regard they write the Sun-climate link on millennial timescales has "been demonstrated in several records (e.g., Bond *et al*., 2001; Hu *et al*., 2003; Niggemann *et al.*, 2003), supporting solar forcing as a plausible mechanism for modulating the AO [Arctic Oscillation]/NAO at millennial timescales."

Dean *et al*. (2002) analyzed the varve thickness and continuous gray-scale density of sediment cores taken from Elk Lake, Minnesota (47°12'N, 95°15'W) for the past 1,500 years. They identified significant periodicities throughout the record, including multidecadal periodicities of approximately 10, 29, 32, 42, and 96 years, and a strong multicentennial periodicity of about 400 years, leading them to wonder whether the observed periodicities are manifestations of solar-induced climate signals, for which they present strong correlative evidence. The 10-year oscillation was found to be strongest in the time series between the fourteenth and nineteenth centuries, during the Little Ice Age, and may have been driven by the 11-year sunspot cycle.

Lozano-Garcia *et al*. (2007) conducted a high-resolution multi-proxy analysis of pollen, charcoal particles, and diatoms found in the sediments of Lago Verde (18°36'46" N, 95°20'52"W)—a small closed-basin lake on the outskirts of the Sierra de Los Tuxtlas (a volcanic field on the coast of the Gulf of Mexico)—which covered the past 2,000 years. The five Mexican researchers say their data "provide evidence that the densest tropical forest cover and the deepest lake of the last two millennia were coeval with the Little Ice Age, with two deep lake phases that follow the Sporer and Maunder minima in solar activity." In addition, they suggest "the high tropical pollen accumulation rates limit the Little Ice Age's winter cooling to a maximum of 2°C," and they conclude the "tropical vegetation expansion during the Little Ice Age is best explained by a reduction in the extent of the dry season as a consequence of increased meridional flow leading to higher winter precipitation." Lozano-Garcia *et al.* conclude, "the data from Lago Verde strongly suggest that during the Little Ice Age lake levels and vegetation at Los Tuxtlas were responding to solar forcing and provide further evidence that solar activity is an important element controlling decadal to centennial scale climatic variability in the tropics (Polissar *et al*., 2006) and in general over the North Atlantic region (Bond *et al*., 2001; Dahl-Jensen *et al*., 1998)."

Hughes *et al.* (2006) derived a multi-proxy palaeoclimate record from Nordan's Pond Bog, a coastal plateau bog in Newfoundland, based on "analyses of plant macrofossils, testate amoebae and the degree of peat humification," enabling them to create "a single composite reconstruction of bog surface wetness (BSW)" they compare with "records of cosmogenic isotope flux."

"At least 14 distinctive phases of increased BSW may be inferred from the Nordan's Pond Bog record," they write, commencing at 8,270 cal. years BP, and "comparisons of the BSW reconstruction with records of cosmogenic isotope flux ... suggest a persistent link between reduced solar irradiance and increased BSW during the Holocene." Hughes *et al.* further conclude the "strong correlation between increased ^{14}C production [which accompanies reduced solar activity] and phases of maximum BSW supports the role of solar forcing as a persistent driver of changes to the atmospheric moisture balance throughout the Holocene." Consequently, the authors state, "evidence suggesting a link between solar irradiance and sub-Milankovitch-scale palaeoclimatic change has mounted" and the "solar hypothesis, as an explanation for Holocene climate change, is now gaining wider acceptance."

Asmerom *et al.* (2007) developed a high-resolution Holocene climate proxy for the southwest United States from δ^{18}O variations in a stalagmite obtained in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw δ^{18}O data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." Their cross-spectral analysis of the Δ^{14}C and δ^{18}O data confirmed the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. They suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

Schmidt *et al.* (2012) found Florida was drier when the Sun was weak and wetter when the Sun was strong. And Nichols *et al.* (2012) note the rains in Maine over the past 7,000 years have been controlled by the sun.

Since the warming of the twentieth century appears to represent the most recent rising phase of the Bond cycle, which in its previous rising phase produced the Medieval Warm Period (see Bond *et al*., 2001), and since we could still be embedded in that rising temperature phase, it is reasonable to expect the desert southwest of the United States could experience more intense aridity while wetter conditions prevail in the monsoon regions of Asia, without greenhouse gases playing any role.

References

Asmerom, Y., Polyak, V., Burns, S., and Rassmussen, J. 2007. Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology* **35**: 1–4.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Chezebiet, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial scale cycle in North-Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.

Cumming, B.F., Laird, K.R., Bennett, J.R., Smol, J.P., and Salomon, A.K. 2002. Persistent millennial-scale shifts in moisture regimes in western Canada during the past six millennia. *Proceedings of the National Academy of Sciences, USA* **99**: 16,117–16,121.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., and Balling, N. 1998. Past temperatures directly from the Greenland Ice Sheet. *Science* **282**: 268–271.

Dean, W., Anderson, R., Bradbury, J.P., and Anderson, D. 2002. A 1500-year record of climatic and environmental change in Elk Lake, Minnesota I: Varve thickness and gray-scale density. *Journal of Paleolimnology* **27**: 287–299.

Hu, F.S., Kaufman, D., Yoneji, S., Nelson, D., Shemesh, A., Huang, Y., Tian, J., Bond, G., Clegg, B., and Brown, T. 2003. Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic. *Science* **301**: 1890–1893.

Hughes, P.D.M., Blundell, A., Charman, D.J., Bartlett, S., Daniell, J.R.G., Wojatschke, A., and Chambers, F.M. 2006. An 8500 cal. year multi-proxy climate record from a bog in eastern Newfoundland: contributions of meltwater discharge and solar forcing. *Quaternary Science Reviews* **25**: 1208–1227.

Kristjansson, J.E., Staple, A., and Kristiansen, J. 2002. A new look at possible connections between solar activity, clouds and climate. *Geophysical Research Letters* **29**: 10.1029/2002GL015646.

Li, Y.-X., Yu, Z., and Kodama, K.P. 2007. Sensitive moisture response to Holocene millennial-scale climate variations in the Mid-Atlantic region, USA. *The Holocene* **17**: 3–8.

Li, Y.-X., Yu, Z., Kodama, K.P., and Moeller, R.E. 2006. A 14,000-year environmental change history revealed by mineral magnetic data from White Lake, New Jersey, USA. *Earth and Planetary Science Letters* **246**: 27–40.

Lozano-Garcia, Ma. del S., Caballero, M., Ortega, B., Rodriguez, A., and Sosa, S. 2007. Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica. *Proceedings of the National Academy of Sciences, USA* **104**: 16,200–16,203.

Nichols, J.E. and Huang, Y. 2012. Hydroclimate of the northeastern United States is highly sensitive to solar forcing. *Geophysical Research Letters* **39**: L04707, doi:10.1029/2011GL050720.

Niggemann, S., Mangini, A., Mudelsee, M., Richter, D.K., and Wurth, G. 2003. Sub-Milankovitch climatic cycles in Holocene stalagmites from Sauerland, Germany. *Earth and Planetary Science Letters* **216**: 539–547.

Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., and Bradley, R.S. 2006. Solar modulation of Little Ice Age climate in the tropical Andes. *Proceedings of the National Academy of Sciences USA* **103**: 8937–8942.

Schmidt, M.W., Weinlein, W.A., Marcantonio, F., and Lynch-Stieglitz, J. 2012. Solar forcing of Florida Straits surface salinity during the early Holocene. *Paleoceanography* **27** doi:10.1029/2012PA002284.

Stuiver, M. and Braziunas, T.F. 1993. Sun, ocean climate and atmospheric $^{14}CO_2$: An evaluation of causal and spectral relationships. *The Holocene* **3**: 289–305.

Udelhofen, P.M. and Cess, R.D. 2001. Cloud cover variations over the United States: An influence of cosmic rays or solar variability? *Geophysical Research Letters* **28**: 2617–2620.

White, W.B., Lean, J., Cayan, D.R., and Dettinger, M.D. 1997. Response of global upper ocean temperature to changing solar irradiance. *Journal of Geophysical Research* **102**: 3255–3266.

3.4.2 South America

Nordemann *et al*. (2005) analyzed tree rings from species sensitive to fluctuations in precipitation from the southern region of Brazil and Chile along with sunspot data via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding of the effects of solar activity, climate, and geophysical phenomena on the continent of South America. The tree-ring samples from Brazil covered 200 years and those from Chile covered 2,500 years. The spectral analysis revealed periodicities in the tree rings that corresponded well with the de Vries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles; wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Baker *et al*. (2005) used a sediment core retrieved from the main basin of Lake Titicaca (16°S, 69°W) on the Altiplano of Bolivia and Peru to reconstruct the lake-level history of that South American water body over the past 13,000 years at decadal to multidecadal resolution based on $\delta^{13}C$ measurements of sediment bulk organic matter. The authors report "the pattern and timing of lake-level change in Lake Titicaca is similar to the ice-rafted debris record of Holocene Bond events, demonstrating a possible coupling between precipitation variation on the Altiplano and North Atlantic sea-surface temperatures." Noting "cold periods of the Holocene Bond events correspond with periods of increased precipitation on the Altiplano," they further conclude "Holocene precipitation variability on the Altiplano is anti-phased with respect to precipitation in the Northern Hemisphere monsoon region." They add, "the relationship between lake-level variation at Lake Titicaca and Holocene Bond events also is supported by the more coarsely resolved (but very well documented) record of water-level fluctuations over the past 4000 years based on the sedimentology of cores from the shallow basin of the lake (Abbott *et al*., 1997)."

Haug *et al*. (2001) utilized the titanium and iron concentrations of an ocean sediment core taken from a depth of 893 meters in the Cariaco Basin on the Northern Shelf of Venezuela (10°42.73'N, 65°10.18'W) to infer variations in the hydrologic cycle over northern South America over the past 14,000 years. They found titanium and iron concentrations were lower during the Younger Dryas cold period between 12.6 and 11.5 thousand years ago, corresponding to a weakened hydrologic cycle with less precipitation and runoff. During the Holocene Optimum (10.5 to 5.4 thousand years ago), concentrations of these metals remained at or near their highest values, suggesting wet conditions and an enhanced hydrologic cycle for more than five thousand years. The largest century-scale variations in precipitation are inferred in the record between approximately 3.8 and 2.8 thousand years ago, as the amounts of these metals in the sediment record varied widely over short time intervals. Higher precipitation was noted during the Medieval Warm Period from 1.05 to 0.7 thousand years ago, followed by drier conditions associated with the Little Ice Age (between 550 and 200 years ago).

The authors say the regional changes in precipitation "are best explained by shifts in the mean latitude of the Atlantic Intertropical Convergence Zone," which, in turn, "can be explained by the Holocene history of insolation, both directly and through its effect on tropical Pacific sea surface conditions."

In South America the Sun has controlled the distribution and intensity of the monsoon rains (Vuille *et al*., 2012), a solar influence on precipitation also has been found for Brazil (Gusec and Martin, 2012; Rampelotto *et al*., 2012), and solar cycles have been detected in the water masses of the deep sea (Seidenglanz *et al*., 2012). The field of research in solar-climate interaction is more active than ever (de Wit *et al*., 2010; Stauning, 2011; Raspopov *et al*., 2011; Kern *et al*., 2012).

References

Abbott, M., Binford, M.B., Brenner, M.W,. and Kelts, K.R. 1997. A 3500 ^{14}C yr high resolution record of lake level changes in Lake Titicaca, South America. *Quaternary Research* **47**: 169–180.

Baker, P.A., Fritz, S.C., Garland, J., and Ekdahl, E. 2005. Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation. *Journal of Quaternary Science* **207**: 655–662.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti- Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

de Wit, T.D. and Watermann, J. 2010. Solar forcing of the terrestrial atmosphere. *Comptes Rendus Geoscience* **342**: 259–272.

Gusev, A.A. and Martin, I.M. 2012. Possible evidence of the resonant influence of solar forcing on the climate system. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 173–178.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Rohl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293**: 1304–1308.

Kern, A. K., Harzhauser, M., Piller, W.E., Mandic, O., and Soliman, A. 2012. Strong evidence for the influence of solar cycles on a Late Miocene lake system revealed by biotic and abiotic proxies. *Palaeogeography, Palaeoclimatology, Palaeoecology* **329/330**: 124–136.

Nordemann, D.J.R., Rigozo, N.R., and de Faria, H.H. 2005. Solar activity and El-Niño signals observed in Brazil and Chile tree ring records. *Advances in Space Research* **35**: 891–896.

Rampelotto, P.H., Rigozo, N.R., da Rosa, M.B., Prestes, A., Frigo, E., Souza Echer, M.P., and Nordemann, D.J.R. 2012. Variability of rainfall and temperature (1912–2008) parameters measured from Santa Maria (29°41′S, 53°48′W) and their connections with ENSO and solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics* **77**: 152–160.

Raspopov, O.M., Dergachev, V.A., Ogurtsov, M.G., Kolström, T., Jungner, H., and Dmitriev, P.B. 2011. Variations in climate parameters at time intervals from hundreds to tens of millions of years in the past and its relation to solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 388–399.

Seidenglanz, A., Prange, M., Varma, V., and Schulz, M. 2012. Ocean temperature response to idealized Gleissberg and de Vries solar cycles in a comprehensive climate model. *Geophysical Research Letters* **39**: L22602, doi:10.1029/2012GL053624.

Stauning, P. 2011. Solar activity–climate relations: A different approach. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1999–2012.

Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H., and Novello, V.F. 2012. A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past* **8**: 1309–1321.

3.4.3 Africa

Neff *et al.* (2001) investigated the relationship between a ^{14}C tree-ring record and a delta^{18}O proxy record of monsoon rainfall intensity as recorded in calcite delta^{18}O data obtained from a stalagmite in northern Oman. The correlation between the two data sets, covering the period 9,600–6,100 years before present, was reported to be "extremely strong." 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 tree-ring records are generally attributed to variations in solar activity and intensity, and because of this particular ^{14}C record's strong correlation with the delta^{18}O record and the closely corresponding results of the spectral analyses, Neff *et al.* conclude there is "solid evidence" that both signals (the ^{14}C and delta^{18}O records) are responding to solar forcing.

Stager *et al.* (2003) studied changes in diatom assemblages preserved in a sediment core extracted from Pilkington Bay, Lake Victoria, together with diatom and pollen data acquired from two nearby sites. According to the authors, the three coherent data sets revealed a "roughly 1400- to 1500-year spacing of century-scale P:E [precipitation: evaporation] fluctuations at Lake Victoria," which "may be related to a ca. 1470-year periodicity in northern marine and ice core records that has been linked to solar variability (Bond *et al.*, 1997; Mayewski *et al.*, 1997)."

Further support of Stager *et al.*'s thesis comes from Verschuren *et al.* (2000), who developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on lake-level and salinity fluctuations of a small crater-lake basin in Kenya, as reconstructed from sediment stratigraphy and the species compositions of fossil diatom and midge assemblages. They compared this history with an equally long record of atmospheric $^{14}CO_2$ production, which is a proxy for solar radiation variations.

They found equatorial east Africa was significantly drier than today during the Medieval Warm Period from AD 1000 to 1270 and relatively wet during the Little Ice Age from AD 1270 to 1850. This latter period was interrupted by three periods of prolonged dryness: 1390–1420, 1560–1625, and 1760–1840. These "episodes of persistent aridity," in the words of the authors, were "more severe than any recorded drought of the twentieth century." They note their results "corroborate findings from north-temperate dryland regions that instrumental climate records are inadequate to appreciate the full range of natural variation in drought intensity at timescales relevant to socio-economic activity." Today, almost every new storm of significant size, every new flood, or every new hint of drought almost anywhere in the world brings claims the weather is becoming more extreme than ever before as a consequence of global warming. Verschuren *et al.* remind us there were more intense droughts in the centuries preceding the recent rise in the atmosphere's CO_2 content.

Verschuren *et al.* discovered "all three severe drought events of the past 700 years were broadly coeval with phases of high solar radiation, and the intervening periods of increased moisture were coeval with phases of low solar radiation." They state variations in solar radiative output "may have contributed to decade-scale rainfall variability in equatorial east Africa." This conclusion is characterized as robust by Oldfield (2000), who suggests their results "provide strong evidence for a link between solar and climate variability."

References

Bond, G., Showers, W., Chezebiet, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial scale cycle in North-Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., and Prentice, M. 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research* **102**: 26,345–26,366.

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.

Oldfield, F. 2000. Out of Africa. *Nature* **403**: 370–371.

Stager, J.C., Cumming, B.F., and Meeker, L.D. 2003. A 10,000-year high-resolution diatom record from Pilkington Bay, Lake Victoria, East Africa. *Quaternary Research* **59**: 172–181.

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

3.4.4 Asia & Australia

Pederson *et al.* (2001) utilized tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for this region over the period 1651–1995.

Analyses of both standard deviations and five-year intervals of extreme wet and dry periods revealed "variations over the recent period of instrumental data are not unusual relative to the prior record" (see Figure 3.4.4.1). The authors state, however, the reconstructions "appear to show more frequent extended wet periods in more recent decades," but they note this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." More important to the present discussion, however, is their observation that spectral analysis of the data revealed significant periodicities of around 12 and 20-24 years, suggesting "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Tan *et al.* (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau's northeast margin since AD 960 based on an analysis of Chinese historical records, which they compared with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories. They found "high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere." They also found "good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record." These findings harmonize, in their words, with "numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene," citing 22 scientific references. The researchers conclude the "synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity."

Paulsen *et al.* (2003) utilized "high-resolution records of δ^{13}C and δ^{18}O in stalagmite SF-1 from Buddha Cave [33°40'N, 109°05'E] ... to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." They identified several major climatic episodes, including the Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and twentieth century warming, "lending support to the global extent of these events." With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet, followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Current Warm Period. Some of the Current Warm Period's variability is undoubtedly due to the much finer one-year time resolution of the past 150 years of the record as compared to the three- to four-year resolution of the prior 1,120 years. The major droughts centered on AD 1835, 1878, and 1955 were very well delineated by this improved resolution.

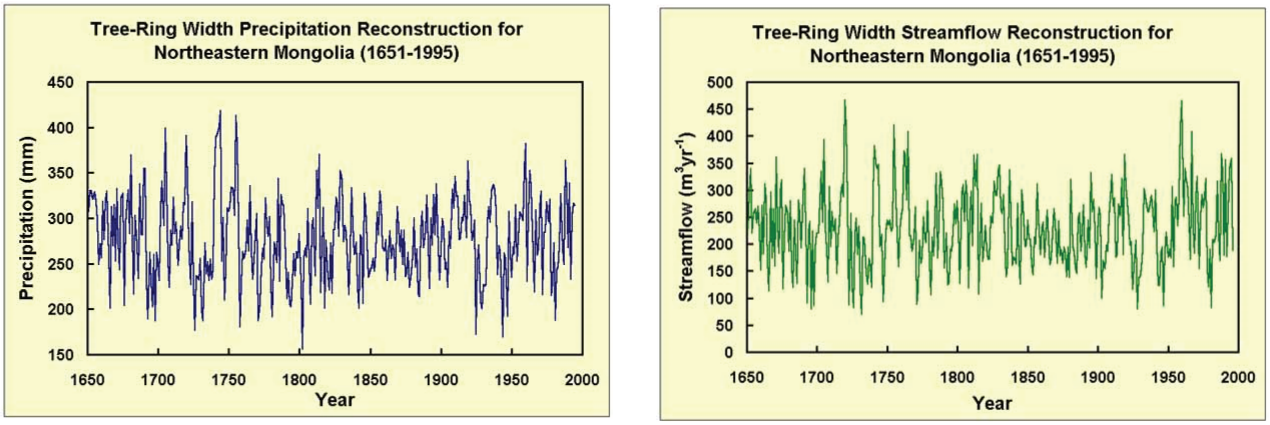

Figure 3.4.4.1. Reconstructed precipitation and streamflow records for northeastern Mongolia over the period 1651-1995. Adapted from Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651-1995. *Journal of Climate* **14**: 872–881.

The data also revealed a number of other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture. Paulsen *et al*. attributed most of these higher-frequency cycles to cyclical solar and lunar phenomena, concluding the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

Liu *et al*. (2012) point out "climate change is consistently associated with changes in a number of components of the hydrological cycle," including "precipitation patterns and intensity, and extreme weather events." To "provide advice for water resource management under climate change," they conducted a study of the subject in the Guangdong Province of Southern China, which occupies a land area of approximately 178,000 km^2 and has a population of just over 96 million people (as of 2009).

Liu *et al*. analyzed "trends of annual, seasonal and monthly precipitation in southern China (Guangdong Province) for the period 1956–2000 ... based on the data from 186 high-quality gauging stations" and employed "statistical tests, including the Mann-Kendall rank test and wavelet analysis" to determine whether the precipitation series exhibited any regular trends or periodicities.

The four researchers report "annual precipitation has a slightly decreasing trend in central Guangdong and slight increasing trends in the eastern and western areas of the province," but "all the annual trends are not statistically significant at the 95% confidence level." In addition, they discovered "average precipitation increases in the dry season in central Guangdong, but decreases in the wet season," such that "precipitation becomes more evenly distributed within the year." They note, "the results of wavelet analysis show prominent precipitation with periods ranging from 10 to 12 years in every sub-region in Guangdong Province." Comparing precipitation with the 11-year sunspot cycle, they find "the annual precipitation in every sub-region in Guangdong province correlates with sunspot Number with a 3-year lag." Liu *et al*.'s analysis suggests precipitation in China's Guangdong Province has become both less extreme and less variable during the 1956–2000 global warming.

Two recent papers by Zhao *et al.* (2012) and Wang and Zhao (2012), scientists at the National Satellite Meteorological Center of China Meteorological Administration, offered practical insights using instrumental records to consider the relationship between solar activity and precipitation. They studied all precipitation records across the whole of China covering all monthly data series but found robust correlations only for the month of June and for specific regions. Wang and Zhao (2012) report:

> Six different statistical methods (i.e., correlation, difference, prominent period, variance contribution, scale-averaged spectrum, and cross spectrum) are used to test for regional differences in the relationship between the 11 year sunspot cycle and June precipitation in China during the 20th century. In the Huaihe River basin (HRB) of central China, located at the marginal region of

> the East Asian summer monsoon (EASM), there exists a reliable positive-correlation relationship between the 11 year sunspot cycle and June precipitation; whereas, possible negative and very weak positive correlations in the south of the middle–lower Yangtze River Region and the HeTao Basin (HTB), located in the interior of the EASM and the westerlies, respectively. The reasons for these regional differences are investigated, revealing that the marginal region of EASM may be more sensitive to solar forcing than is its interior, which results in the HRB becoming the most susceptible (strongest correlation) region. That is to say, in June during the high sunspot number (SSN) years, the influence of the EASM is significantly greater and more to the north than that in June during the low SSN years, causing the HRB to be mainly influenced by the EASM (westerlies) in June during the high (low) SSN years. The northward expansion of the June EASM probably resulted from enhancement of the low-level southwesterly monsoon flow over the northern tropical Indian Ocean, combined with an expansion of the western Pacific subtropical high at times of high SSN.

Further research confirms the solar-climate link with respect to precipitation. In China's Taklimakan Desert, oases blossomed in sync with solar millennial scale cycles (Zhao *et al*., 2012), and temperatures on the Tibetan plateau followed the sun's moods (Liu *et al*., 2011). Yu *et al*. (2012) found the East Asian monsoon to be controlled by solar activity changes, while Wu *et al*. (2012) found water currents of the East China Sea varied according to the sun's behavior. The climate of the Baikal Lake was shown by Murakami *et al*. (2012) to be correlated with solar activity, and the rains in Southeast Australia were in sync with the solar pattern (Kemp *et al*., 2012). Natural climate cycles appear to have led to the collapse of the powerful Indus Civilization (Giosan *et al*., 2012).

The Indian monsoons have strengthened and weakened according to the rhythm of the sun over the past 150 years (van Loon and Meehl, 2012). Rains on the Tibetan Plateau stopped whenever the sun weakened (Sun and Liu, 2012). Corals in Japan died during cold phases triggered by low solar activity (Hamanaka *et al*., 2012). A marked solar influence on Japanese climate was found in studies by Yamaguchi *et al*. (2010) and Muraki *et al*. (2011). Wet phases in Lake Aral were associated with solar high activity phases (Huang *et al*., 2011).

Precipitation in Asia clearly is determined by cycles, many of which are solar-driven and nearly all of which are independent of the air's CO_2 concentration.

References

Giosan, L., Clift, P.D., Macklin, M.G., Fuller, D.Q., Constantinescu, S., Durcan, J.A., Stevens, T., Duller, G.A.T., Tabrez, A.R., Gangal, K., Adhikari, R., Alizai, A., Filip, F., VanLaningham, S., and Syvitski, J.P.M. 2012. Fluvial landscapes of the Harappan civilization. *Proceedings of the National Academy of Sciences* doi: 10.1073/pnas.1112743109.

Kemp, J., Radke, L.C., Olley, J., Juggins, S., and De Deckker, P. 2012. Holocene lake salinity changes in the Wimmera, southeastern Australia, provide evidence for millennial-scale climate variability. *Quaternary Research* **77**: 65–76.

Hamanaka, N., Kan, H., Yokoyama, Y., Okamoto, T., Nakashima, Y., and Kawana, T. 2012. Disturbances with hiatuses in high-latitude coral reef growth during the Holocene: Correlation with millennial-scale global climate change. *Global and Planetary Change* **80/81**: 21–35.

Huang, X., Oberhänsli, H., von Suchodoletz, H., and Sorrel, P. 2011. Dust deposition in the Aral Sea: implications for changes in atmospheric circulation in central Asia during the past 2000 years. *Quaternary Science Reviews* **30**: 3661–3674.

Liu, D., Guo, S., Chen, X., and Shao, Q. 2012. Analysis of trends of annual and seasonal precipitation from 1956 to 2000 in Guangdong Province, China. *Hydrological Sciences Journal* **57**: 358–369.

Liu, Y., Cai, Q.-F., Song, H.-M., An, Z.-S., and Linderholm, H.W. 2011. Amplitudes, rates, periodicities and causes of temperature variations in the past 2485 years and future trends over the central-eastern Tibetan Plateau. *Chinese Science Bulletin* **56**: 2986–2994.

Murakami, T., Takamatsu, T., Katsuta, N., Takano, M., Yamamoto, K., Takahashi, Y., Nakamura, T., and Kawai, T. 2012. Centennial- to millennial-scale climate shifts in continental interior Asia repeated between warm–dry and cool–wet conditions during the last three interglacial states: evidence from uranium and biogenic silica in the sediment of Lake Baikal, southeast Siberia. *Quaternary Science Reviews* **52**: 49–59.

Muraki, Y., Masuda, K., Nagaya, K., Wada, K., and Miyahara, H. 2011. Solar variability and width of tree ring. *Astrophysics and Space Sciences Transactions* **7**: 395–401.

Paulsen, D.E., Li, H.-C., and Ku, T.-L. 2003. Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records. *Quaternary Science Reviews* **22**: 691–701.

Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651-1995. *Journal of Climate* **14**: 872–881.

Sun, J. and Liu, Y. 2012. Tree ring based precipitation reconstruction in the south slope of the middle Qilian Mountains, northeastern Tibetan Plateau, over the last millennium. *Journal of Geophysical Research* **117**: D08108, doi:10.1029/2011JD017290.

Tan, L., Cai, Y., An, Z., and Ai, L. 2008. Precipitation variations of Longxi, northeast margin of Tibetan Plateau since AD 960 and their relationship with solar activity. *Climate of the Past* **4**: 19–28.

van Loon, H. and Meehl, G.A. 2012. The Indian summer monsoon during peaks in the 11 year sunspot cycle. *Geophysical Research Letters* **39**: L13701, doi:10.1029/2012GL051977.

Wang, J. and Zhao, L. 2012. Statistical tests for a correlation between decadal variation in June precipitation in China and sunspot number. *Journal of Geophysical Research* **117**: 10.1029/2012JD018074.

Wu, W., Tan, W., Zhou, L., Yang, H., and Xu, Y. 2012. Sea surface temperature variability in southern Okinawa Trough during last 2700 years. *Geophysical Research Letters* **39**: L14705, doi:10.1029/2012GL052749.

Yamaguchi, Y.T., Yokoyama, Y., Miyahara, H., Sho, K., and Nakatsuka, T. 2010. Synchronized Northern Hemisphere climate change and solar magnetic cycles during the Maunder Minimum. *Proceedings of the National Academy of Sciences* **107**: 20,697–20,702.

Yu, F., Zong, Y., Lloyd, J.M., Leng, M.J., Switzer, A.D., Yim, W.W.-S, and Huang, G. 2012. Mid-Holocene variability of the East Asian monsoon based on bulk organic $\delta^{13}C$ and C/N records from the Pearl River estuary, southern China. *The Holocene* **22**: 705–715.

Zhao, L., Wang, J., and Zhao, H. 2012. Solar cycle signature in decadal variability of monsoon precipitation in China. *Journal of the Meteorological Society of Japan* **90**: 1–9.

Zhao, K., Li, X., Dodson, J., Atahan, P., Zhou, X., and Bertuch, F. 2012. Climatic variations over the last 4000 yr BP in the western margin of the Tarim Basin, Xinjiang, reconstructed from pollen data. *Palaeogeography, Palaeoclimatology, Palaeoecology* **321/322**: 16–23.

3.4.5 Europe

Mauquoy *et al.* (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes of climate change during the Holocene. They report "analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al.* (1995), van Geel *et al.* (1996), Speranza *et al.* (2000), Speranza (2000) and Mauquoy *et al.* (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977)." This close correspondence suggests "changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al.*, 1996, 1998, 1999, 2000) and the 'Little Ice Age' series of palaeoclimatic changes."

With respect to how the Sun may have driven the changes, the European scientists suggest two possibilities: "increased cosmic ray intensity, stimulating cloud formation and precipitation (Svensmark and FriisChristensen, 1997)," and "reduced solar UV intensity, causing a decline of stratospheric ozone production and cooling as a result of less absorption of sunlight (Haigh, 1996, 2001)." Noting "modeling results of Shindell *et al.* (2001) suggest solar-induced variations of ozone production could drive temperature changes in the middle and lower atmospheres, which in turn could cause changes in the North Atlantic Oscillation and the Arctic Oscillation," they tentatively conclude the solar UV mechanism may be the more likely of the two possibilities.

Blaauw *et al.* (2004) point out "Raised bogs are dependent on precipitation alone for water and nutrients," and each of the species of plants found in them have specific requirements with respect to depth of water table. As a result, the vertical distribution of macro- and micro-fossils in raised bogs reveals much about past changes in local moisture conditions, especially, the authors note, "about changes in effective precipitation (precipitation minus evapo-transpiration)." At the same time, changes in the carbon-14 content of bog deposits reveal something about solar activity, because, as Blaauw *et al.* describe the connection, "a decreased solar activity leads to less solar wind, reduced shielding against cosmic rays, and thus to increased production of cosmogenic isotopes [such as ^{14}C]." Consequently, it is possible to compare the histories of the two records (effective precipitation and $\delta^{14}C$) and see if inferred changes in climate bear any relationship to inferred changes in solar activity.

Two cores of mid-Holocene raised-bog deposits in the Netherlands were ^{14}C "wiggle-match" dated by the authors at high precision, using the technique described by Kilian *et al.* (1995, 2000) and Blaauw *et al.* (2003), and changes in local moisture conditions were inferred from the changing species composition of consecutive series of macrofossil samples. They found nine of 11 major mid-Holocene δ^{14}C increases, "probably caused by declines in solar activity," were coeval with major wet-shifts "probably caused by climate getting cooler and/or wetter." In the case of the significant wet-shift at the major δ^{14}C rise in the vicinity of 850 BC, they note this prominent climatic cooling has been independently documented in many parts of the world, including "the North Atlantic Ocean (Bond *et al*., 2001), the Norwegian Sea (Calvo *et al*., 2002) [see also Andersson *et al.* (2003)], Northern Norway (Vorren, 2001), England (Waller *et al*., 1999), the Czech Republic (Speranza *et al*., 2000, 2002), central southern Europe (Magny, 2004), Chile (van Geel *et al*., 2000), New Mexico (Armour *et al*., 2002) and across the continent of North America (Viau *et al*., 2002)."

Blaauw *et al.* (2003) say their findings "add to the accumulating evidence that solar variability has played an important role in forcing climatic change during the Holocene."

Cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen) by Björck and Clemmensen (2004) were examined for their content of wind-transported clastic material via a systematic count of quartz grains of diameter 0.2–0.35 mm and larger than 0.35 mm to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter storminess in that part of the world. According to the authors, "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." They note "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," while "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

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

Several researchers have studied the precipitation histories of regions along the Danube River in western Europe and their effects on river discharge, with some suggesting an anthropogenic signal is present in the latter decades of the twentieth century and is responsible for that period's drier conditions. Ducic (2005) examined such claims by analyzing observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He notes the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was practically equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. In addition, the discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be "completely inside the limits of the whole series" and only slightly (38 m^3s^{-1} or 0.7 percent) less than the 260-year mean of 5356 m^3s^{-1}. Ducic concludes "modern discharge fluctuations do not point to [a] dominant anthropogenic influence." His correlative analysis suggests the detected cyclicity in the record could "point to the domination of the influence of solar activity."

Holzhauser *et al.* (2005) present high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, the northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year temperature and precipitation climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest of all glaciers located in the European Alps.

Near the beginning of the period studied, the three researchers report "during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today," noting "the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al.*, 2003)." After an intervening unnamed cold-wet phase, when the glacier grew in both mass and length, they state, "during the Iron/Roman Age Optimum between c. 200 BC and AD 50," perhaps better known as the Roman Warm Period, the glacier again retreated and "reached today's extent or was even somewhat shorter than today." Next came the Dark Ages Cold Period followed by "the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300." They note the latter cold-wet phase was "characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60," following which the glacier began its latest and still-ongoing recession in 1865.

Data pertaining to the Gorner glacier (the second largest of the Swiss Alps) and the Lower Grindelwald glacier of the Bernese Alps tell much the same story, Holzhauser *et al.* report these glaciers and the Great Aletsch glacier "experienced nearly synchronous advances" throughout the study period. The Swiss and French scientists report "glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity," which in their estimation "suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlén, 1973; Magny, 1993; van Geel *et al.*, 1996; Bond *et al.*, 2001)." They conclude by stating "a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene."

Lamy *et al.* (2006) used paleoenvironmental proxy data for ocean properties, eolian sediment input, and continental rainfall based on high-resolution analyses of sediment cores from the southwestern Black Sea and the northernmost Gulf of Aqaba to infer hydroclimatic changes in northern Anatolia and the northern Red Sea region during the last ~7500 years. That reconstructed hydroclimatic history was compared with Δ^{14}C periodicities evident in the tree-ring data of Stuiver *et al.* (1998). The researchers found "pronounced and coherent" multicentennial variations they conclude "strongly resemble modern temperature and rainfall anomalies related to the Arctic Oscillation/North Atlantic Oscillation (AO/NAO)." In addition, they state "the multicentennial variability appears to be similar to changes observed in proxy records for solar output changes," although "the exact physical mechanism that transfers small solar irradiance changes either to symmetric responses in the North Atlantic circulation or to atmospheric circulation changes involving an AO/NAO-like pattern, remains unclear."

In 2012 Dermody *et al.* found solar-driven millennial scale cycles controlled wet and drought phases in the Mediterranean region during Roman times.

Each of these studies indicates cyclical solar activity induces cyclical precipitation activity in Europe. As Lamy *et al.* (2006) note, "the impact of (natural) centennial-scale climate variability on future climate projections could be more substantial than previously thought."

References

Andersson, C., Risebrobakken, B., Jansen, E., and Dahl, S.O. 2003. Late Holocene surface ocean conditions of the Norwegian Sea (Voring Plateau). *Paleoceanography* **18**: 10.1029/2001PA000654.

Armour, J., Fawcett, P.J., and Geissman, J.W. 2002. 15 k.y. palaeoclimatic and glacial record from northern New Mexico. *Geology* **30**: 723–726.

Björck, S. and Clemmensen, L.B. 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene* **14**: 677–688.

Blaauw, M., Heuvelink, G.B.M., Mauquoy, D., van der Plicht, J., and van Geel, B. 2003. A numerical approach to ^{14}C wiggle-match dating of organic deposits: best fits and confidence intervals. *Quaternary Science Reviews* **22**: 1485–1500.

Blaauw, M., van Geel, B., and van der Plicht, J. 2004. Solar forcing of climatic change during the mid-Holocene: indications from raised bogs in The Netherlands. *The Holocene* **14**: 35–44.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Calvo, E., Grimalt, J., and Jansen, E. 2002. High resolution U_{37}^{K} sea temperature reconstruction in the Norwegian Sea during the Holocene. *Quaternary Science Reviews* **21**: 1385–1394.

Denton, G.H. and Karlén, W. 1973. Holocene climate variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.

Dermody, B.J., de Boer, H.J., Bierkens, M.F.P., Weber, S.L., Wassen, M.J., and Dekker, S.C. 2012. A seesaw in Mediterranean precipitation during the Roman Period linked to millennial-scale changes in the North Atlantic. *Climate of the Past* **8**: 637–651

Ducic, V. 2005. Reconstruction of the Danube discharge on hydrological station Orsova in pre-instrumental period: Possible causes of fluctuations. *Edition Physical Geography of Serbia* **2**: 79–100.

Haigh, J.D. 1996. The impact of solar variability on climate. *Science* **272**: 981–984.

Haigh, J.D. 2001. Climate variability and the influence of the sun. *Science* **294**: 2109–2111.

Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* **15**: 789–801.

Kilian, M.R., van der Plicht, J., and van Geel, B. 1995. Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* **14**: 959–966.

Kilian, M.R., van Geel, B., and van der Plicht, J. 2000. ^{14}C AMS wiggle matching of raised bog deposits and models of peat accumulation. *Quaternary Science Reviews* **19**: 1011–1033.

Kilian, M.R., van der Plicht, J., and van Geel, B. 1995. Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* **14**: 959–966.

Lamy, F., Arz, H.W., Bond, G.C., Bahr, A., and Patzold, J. 2006. Multicentennial-scale hydrological changes in the Black Sea and northern Red Sea during the Holocene and the Arctic/North Atlantic Oscillation. *Paleoceanography* **21**: 10.1029/2005PA001184l.

Magny, M. 1993. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* **40**: 1–9.

Magny, M. 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations, and its probable impact on prehistoric human settlements. *Quaternary International* **113**: 65–79.

Mauquoy, D., Engelkes, T., Groot, M.H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J., and van Geel, B. 2002a. High resolution records of late Holocene climate change and carbon accumulation in two north-west European ombrotrophic peat bogs. *Palaeogeography, Palaeoclimatology, Palaeoecology 186*: 275–310.

Mauquoy, D., van Geel, B., Blaauw, M., and van der Plicht, J. 2002b. Evidence from North-West European bogs shows 'Little Ice Age' climatic changes driven by changes in solar activity. *The Holocene* **12**: 1–6.

Mauquoy, D., van Geel, B., Blaauw, M., Speranza, A., and van der Plicht, J. 2004. Changes in solar activity and Holocene climatic shifts derived from ^{14}C wiggle-match dated peat deposits. *The Holocene* **14**: 45–52.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., and Waple, A. 2001. Solar forcing of regional climate change during the Maunder Minimum. *Science* **294**: 2149–2152.

Speranza, A. 2000. Solar and Anthropogenic Forcing of Late-Holocene Vegetation Changes in the Czech Giant Mountains. PhD thesis. University of Amsterdam, Amsterdam, The Netherlands.

Speranza, A.O.M., van der Plicht, J., and van Geel, B. 2000. Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching. *Quaternary Science Reviews* **19**: 1589–1604.

Speranza, A.O.M., van Geel, B., and van der Plicht, J. 2002. Evidence for solar forcing of climate change at ca. 850 cal. BC from a Czech peat sequence. *Global and Planetary Change* **35**: 51–65.

Stuiver, M. and Polach, H.A. 1977. Discussion: reporting ^{14}C data. *Radiocarbon* **19**: 355–363.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., and Spurk, M. 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal PB. *Radiocarbon* **40**: 1041–1083.

Svensmark, H. and Friis-Christensen, E. 1997. Variation of cosmic ray flux and global cloud coverage—a missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics* **59**: 1225–1232.

Tinner, W., Lotter, A.F., Ammann, B., Condera, M., Hubschmied, P., van Leeuwan, J.F.N., and Wehrli, M. 2003. Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to AD 800. *Quaternary Science Reviews* **22**: 1447–1460.

van Geel, B., Buurman, J., and Waterbolk, H.T. 1996. Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science* **11**: 451–460.

van Geel, B., Heusser, C.J., Renssen, H., and Schuurmans, C.J.E. 2000. Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis. *The Holocene* **10**: 659–664.

van Geel, B., Raspopov, O.M., Renssen, H., van der Plicht, J., Dergachev, V.A., and Meijer, H.A.J. 1999. The role of solar forcing upon climate change. *Quaternary Science Reviews* **18**: 331–338.

van Geel, B., van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M., Renssen, H., Reynaud-Farrera, I., and Waterbolk, H.T. 1998. The sharp rise of delta ^{14}C c. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* **40**: 535–550.

Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E., and Sawada, M.C. 2002. Widespread evidence of 1500 yr climatic variability in North America during the past 14000 yr. *Geology* **30**: 455–458.

Vorren, K.-D. 2001. Development of bogs in a coast-inland transect in northern Norway. *Acta Palaeobotanica* **41**: 43–67.

Waller, M.P., Long, A.J., Long, D., and Innes, J.B. 1999. Patterns and processes in the development of coastal mire vegetation multi-site investigations from Walland Marsh, Southeast England. *Quaternary Science Reviews* **18**: 1419–1444.

3.5 Other Climatic Variables

In the previous two sections of this chapter we examined empirical observations of a solar influence on temperature and precipitation. In this section we examine empirical observations of the Sun's influence on other climate variables, including droughts, floods, monsoons, and streamflow.

3.5.1 Droughts

The IPCC claims Earth's climate is becoming more variable and extreme as a result of CO_2-induced global warming, and it forecasts increasing length and severity of drought as one of the consequences. In Chapter 7 of this report, addressing extreme weather, we will present evidence that modern drought frequency and severity fall well within the range of natural variability. Here, we consider the issue of attribution, specifically investigating the natural influence of the Sun on drought. We begin with a review of the literature on droughts in the United States.

According to Cook *et al*. (2007), recent advances in the reconstruction of past drought periods over North America "have revealed the occurrence of a number of unprecedented megadroughts over the past millennium that clearly exceed any found in the instrumental records." They state "these past megadroughts dwarf the famous droughts of the twentieth century, such as the Dust Bowl drought of the 1930s, the southern Great Plains drought of the 1950s, and the current one in the West that began in 1999." These dramatic droughts pale when compared to "an epoch of significantly elevated aridity that persisted for almost 400 years over the AD 900–1300 period," they write.

Of central importance to North American drought formation "is the development of cool 'La Niña-like' SSTs in the eastern tropical Pacific," the note. Paradoxically, as they describe the situation, "warmer conditions over the tropical Pacific region lead to the development of cool La Niña-like SSTs there, which is drought inducing over North America." In further explaining the mechanics of this phenomenon, on which both "model and data agree," Cook *et al*. state, "if there is a heating over the entire tropics then the Pacific will warm more in the west than in the east because the strong upwelling and surface divergence in the east moves some of the heat poleward"; as a result, "the east-west temperature gradient will strengthen, so the winds will also strengthen, so the temperature gradient will increase further, ... leading to a more La Niña-like state." They add "La Niña-like conditions were apparently the norm during much of the Medieval period when the West was in a protracted period of elevated aridity and solar irradiance was unusually high."

Yu and Ito (1999) studied a sediment core from a closed-basin lake in the northern Great Plains of North America, producing a 2,100-year record that revealed four dominant periodicities of drought matching "in surprising detail" similar periodicities of various solar indices. The correspondence was so close, they state "this spectral similarity forces us to consider solar variability as the major cause of century-scale drought frequency in the northern Great Plains."

Dean and Schwalb (2000) derived a similar-length record of drought from sediment cores extracted from Pickerel Lake, South Dakota, which also exhibited recurring incidences of major drought on the northern Great Plains. They too reported the cyclical behavior appeared to be synchronous with variations in solar irradiance. After making a case for "a direct connection between solar irradiance and weather and climate," they conclude "it seems reasonable that the cycles in aridity and eolian activity over the past several thousand years recorded in the sediments of lakes in the northern Great Plains might also have a solar connection."

Springer *et al*. (2008) derived a multidecadal-scale record of Holocene drought based on Sr/Ca ratios and δ^{13}C data obtained from stalagmite BCC-002 from Buckeye Creek Cave (BCC), West Virginia (USA) that "grew continuously from ~7000 years B.P. to ~800 years B.P." and then again "from ~800 years B.P. until its collection in 2002."

They identified seven significant mid- to late-Holocene droughts, six of which "correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle" (see Bond *et al*., 2001). In addition, they determined the Sr/Ca and δ^{13}C time series "display periodicities of ~200 and ~500 years and are coherent in those frequency bands." They also state, "the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle," and they "interpret the ~500-year periodicity to be a harmonic of the IRD oscillations." Noting "cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years," they observe "these latter values are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity." The five researchers conclude their findings "corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau *et al*., 2002; Willard *et al*., 2005; Denniston *et al*., 2007)," adding their high-resolution time series now provide even stronger evidence "in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results."

Mensing *et al*. (2004) inferred the hydrological history of the Pyramid Lake, Nevada area by analyzing a set of sediment cores for pollen and algal microfossils deposited in the lake over the past 7,630 years. According to the authors, "sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet," but "the past 2500 yr have been marked by recurring persistent droughts." The longest of these droughts, they found, "occurred between 2500 and 2000 cal yr B.P.," and others occurred "between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P." They note "the timing and magnitude of droughts identified in the pollen record compares favorably with previously published δ^{18}O data from Pyramid Lake" and with "the ages of submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada." They compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice (Bond *et al.,* 2001) and, like other researchers, found "nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record." Mensing *et al.* conclude "changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States]."

Asmerom *et al*. (2007) developed a high-resolution climate proxy for the southwest United States from δ^{18}O variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw δ^{18}O data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." They report cross-spectral analysis of the Δ^{14}C and δ^{18}O data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

Hodell *et al*. (2001) analyzed sediment cores obtained from Lake Chichancanab on the Yucatan Peninsula of Mexico, reconstructing the climatic history of this region over the past 2,600 years. Long episodes of drought were noted throughout the record, and spectral analysis revealed a significant periodicity that matched well with a cosmic ray-produced ^{14}C record preserved in tree rings believed to reflect variations in solar activity. They concluded "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

Black *et al.* (1999) found evidence of substantial decadal and centennial climate variability in a study of ocean sediments deposited in the southern Caribbean over the past 825 years. Their data suggest climate regime shifts are a natural aspect of Atlantic variability. They conclude "these shifts may play a role in triggering changes in the frequency and persistence of drought over North America." Because there was a strong correspondence between these phenomena and similar changes in ^{14}C production rate, they conclude "small changes in solar output may influence Atlantic variability on centennial time scales."

Helama *et al.* (2009) used regional curve standardization (RCS) procedures with data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland to develop what they describe as "the first European dendroclimatic precipitation reconstruction," which "covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP)," from AD 670 to AD 1993. They find "the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD." This interval, they write, "precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture." In addition, they report "the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930)."

The three Finnish scientists note the global medieval drought they discovered "occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook *et al*., 2004, 2007), eastern South America (Stine, 1994; Rein *et al*., 2004), and equatorial East Africa (Verschuren *et al*., 2000; Russell and Johnson, 2005a, 2007; Stager *et al*., 2005) between AD 900 and 1300." Noting this widespread evidence "argues for a common force behind the hydrological component of the MCA," they note "previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren *et al*., 2000; Stager *et al*., 2005) or the ENSO (Cook *et al*., 2004, 2007; Rein *et al*., 2004; Herweijer *et al*., 2006, 2007; Graham *et al*., 2007, Seager *et al*., 2007)," stating "the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the Δ^{14}C and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki *et al*., 2004)."

Verschuren *et al.* (2000) conducted a similar study of a small lake in Kenya, documenting the existence of three periods of prolonged dryness during the Little Ice Age that were, in their words, "more severe than any recorded drought of the twentieth century." They discovered all three of these severe drought events "were broadly coeval with phases of high solar radiation," as inferred from ^{14}C production data, "and the intervening periods of increased moisture were coeval with phases of low solar radiation." They concluded variations in solar activity "may have contributed to decade-scale rainfall variability in equatorial east Africa."

Also in Africa, working with three sediment cores extracted from Lake Edward (0°N, 30°E), Russell and Johnson (2005b) developed a continuous 5,400-year record of Mg concentration and isotopic composition of authigenic inorganic calcite as proxies for the lake's water balance, which is itself a proxy for regional drought conditions in equatorial Africa. They found "the geochemical record from Lake Edward demonstrates a consistent pattern of equatorial drought during both cold and warm phases of the North Atlantic's '1500-year cycle' during the late Holocene," noting similar "725-year climate cycles" are found in several records from the Indian and western Pacific Oceans and the South China Sea, citing the studies of von Rad *et al.* (1999), Wang *et al.* (1999), Russell *et al.* (2003), and Staubwasser *et al.* (2003). Russell and Johnson state their results "show that millennial-scale high-latitude climate events are linked to changes in equatorial terrestrial climate ... during the late Holocene" and "suggest a spatial footprint in the tropics for the '1500-year cycle' that may help to provide clues to discern the cycle's origin," noting there is reason to believe it may be solar-induced.

Garcin *et al.* (2007) explored hydrologic change using late-Holocene paleoenvironmental data derived from several undisturbed sediment cores retrieved from the deepest central part of Lake Masoko (9°20.0'S, 33°45.3'E), which occupies a maar crater in the Rungwe volcanic highlands of the western branch of Africa's Rift Valley, approximately 35 km north of Lake Malawi. According to the ten researchers, "magnetic, organic carbon, geochemical proxies and pollen assemblages indicate a dry climate during the 'Little Ice Age' (AD 1550–1850), confirming that the LIA in eastern Africa resulted in marked and synchronous hydrological changes," although "the direction of response varies between different African lakes."

They report "to the south (9.5-14.5°S), sediment cores from Lake Malawi have revealed similar climatic conditions (Owen *et al*., 1990; Johnson *et al*., 2001; Brown and Johnson, 2005)" "correlated with the dry period of Lakes Chilwa and Chiuta (Owen and Crossley, 1990)." They further note "lowstands have been also observed during the LIA at Lake Tanganyika ... from AD 1500 until AD 1580, and from ca. AD 1650 until the end of the 17th century, where the lowest lake-levels are inferred (Cohen *et al*., 1997; Alin and Cohen, 2003)." By contrast, they report "further north, evidence from Lakes Naivasha (0.7°S) and Victoria (2.5°S-0.5°N) indicates relatively wet conditions with high lake-levels during the LIA, interrupted by short drought periods (Verschuren *et al*., 2000; Verschuren, 2004; Stager *et al*., 2005)."

Garcin *et al*. also note, "inferred changes of the Masoko hydrology are positively correlated with the solar activity proxies." The African and French scientists say the Little Ice Age in Africa appears to have had a greater thermal amplitude than it did in the Northern Hemisphere, citing in support of this statement the paleoclimate studies of Bonnefille and Mohammed (1994), Karlén *et al*. (1999), Holmgren *et al*. (2001), and Thompson *et al*. (2002). Nevertheless, the more common defining parameter of the Little Ice Age in Africa was the moisture status of the continent, which appears to have manifested opposite directional trends in different latitudinal bands. In addition, the group of scientists emphasizes the positive correlation of Lake Masoko hydrology with various solar activity proxies "implies a forcing of solar activity on the atmospheric circulation and thus on the regional climate of this part of East Africa."

Trouet *et al*. (2009) describe in *Science* how they constructed a 947-year history (AD 1049–1995) of the North Atlantic Oscillation (NAO), using a tree-ring-based drought reconstruction for Morocco (Esper *et al*., 2007) and a speleothem-based precipitation proxy for Scotland (Proctor *et al*., 2000). This history begins in the midst of what they call the Medieval Climate Anomaly (MCA), "a period (~ AD 800-1300) marked by a wide range of changes in climate globally." This interval of medieval warmth, as they describe it, is "the most recent natural counterpart to modern warmth and can therefore be used to test characteristic patterns of natural versus anthropogenic forcing."

The results of their work are shown in Figure 3.5.1.1. The peak strength of the NAO during the MCA is shown to have been essentially equivalent to the peak strength the NAO has so far manifested during the Current Warm Period (CWP). This finding suggests the peak warmth of the MCA was also likely equivalent to the peak warmth of the CWP.

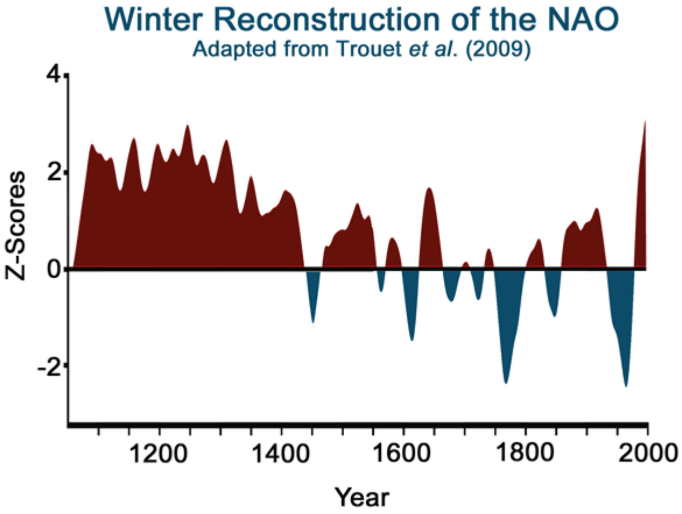

Figure 3.5.1.1. Winter reconstruction of the NAO for the period AD 1049-1995 based on a tree-ring-proxy drought reconstruction for Morocco and a speleothem-based precipitation proxy for Scotland. Adapted from Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* **324**: 78–80.

To explain their findings, Trouet *et al*. propose "the increased pressure difference between the Azores High and the Icelandic Low during positive NAO phases results in enhanced zonal flow, with stronger westerlies transporting warm air to the European continent," to which they add "stronger westerlies associated with a positive NAO phase may have enhanced the Atlantic meridional overturning circulation (AMOC)," which in turn may have generated "a related northward migration of the intertropical convergence zone." What initiated these phenomena? Trouet *et al*. write, "the persistent positive phase [of the NAO] reconstructed for the

MCA appears to be associated with prevailing La Niña-like conditions possibly initiated by enhanced solar irradiance and/or reduced volcanic activity and amplified and prolonged by enhanced AMOC."

Barker's (2008) analysis of data from 1876 to the present suggests when the Sun's South Pole is positive in the Hale Cycle, the likelihood of strongly positive and negative Southern Oscillation Index (SOI) values increase after certain phases in the cyclic ~22-year solar magnetic field. The SOI is also shown to track the pairing of sunspot cycles in ~88-year periods. This coupling of odd cycles—23–15, 21–13, and 19–11—produces an apparently close charting of positive and negative SOI fluctuations for each grouping. This Gleissberg effect is also apparent in the southern hemisphere rainfall anomaly. Over the past decade, the SOI and rainfall fluctuations have been tracking values similar to those recorded in Cycle 15 (1914–1924). This discovery may have important implications for future drought predictions in Australia and in countries in the Northern and Southern Hemisphere, which have been shown to be influenced by the sunspot cycle. Further, it provides a benchmark for long-term SOI behaviour.

There seems to be little question that variations in solar activity have been responsible for much of the drought variability of the Holocene in many parts of the world.

References

Alin, S.R. and Cohen, A.S. 2003. Lake-level history of Lake Tanganyika, East Africa, for the past 2500 years based on ostracod-inferred water-depth reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology* **1999**: 31–49.

Asmerom, Y., Polyak, V., Burns, S., and Rassmussen, J. 2007. Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology* **35**: 1–4.

Baker, R.G.V. 2008. Exploratory analysis of similarities in solar cycle magnetic phases with Southern Oscillation Index fluctuations in Eastern Australia. *Geographical Research* **46**: 380–398, doi: 10.1111/j.1745-5871.2008.00537.x

Black, D.E., Peterson, L.C., Overpeck, J.T., Kaplan, A., Evans, M.N., and Kashgarian, M. 1999. Eight centuries of North Atlantic Ocean atmosphere variability. *Science* **286**: 1709–1713.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bonnefille, R. and Mohammed, U. 1994. Pollen-inferred climatic fluctuations in Ethiopia during the last 2000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* **109**: 331–343.

Brown, E.T. and Johnson, T.C. 2005. Coherence between tropical East African and South American records of the Little Ice Age. *Geochemistry, Geophysics, Geosystems* **6**: 10.1029/2005GC000959.

Cohen, A.S., Talbot, M.R., Awramik, S.M., Dettmen, D.L,. and Abell, P. 1997. Lake level and paleoenvironmental history of Lake Tanganyika, Africa, as inferred from late Holocene and modern stromatolites. *Geological Society of American Bulletin* **109**: 444–460.

Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American drought: Reconstructions, causes, and consequences. *Earth-Science Reviews* **81**: 93–134.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Dean, W.E. and Schwalb, A. 2000. Holocene environmental and climatic change in the Northern Great Plains as recorded in the geochemistry of sediments in Pickerel Lake, South Dakota. *Quaternary International* **67**: 5–20.

Denniston, R.F., DuPree, M., Dorale, J.A., Asmerom, Y., Polyak, V.J., and Carpenter, S.J. 2007. Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central Missouri, USA. *Quaternary Research* **68**: 45–52.

Esper, J., Frank, D., Buntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E. 2007. Long-term drought severity variations in Morocco. *Geophysical Research Letters* **34**: 10.1029/2007GL030844.

Garcin, Y., Williamson, D., Bergonzini, L., Radakovitch, O., Vincens, A., Buchet, G., Guiot, J., Brewer, S., Mathe, P.-E., and Majule, A. 2007. Solar and anthropogenic imprints on Lake Masoko (southern Tanzania) during the last 500 years. *Journal of Paleolimnology* **37**: 475–490.

Graham, N., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., and Xu, T. 2007. Tropical Pacific-mid-latitude teleconnections in medieval times. *Climatic Change* **83**: 241–285.

Helama, S., Merilainen, J., and Tuomenvirta, H. 2009. Multicentennial megadrought in northern Europe coincided with a global El Niño-Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* **37**: 175–178.

Herweijer, C., Seager, R., and Cook, E.R. 2006. North American droughts of the mid to late nineteenth century: History, simulation and implications for Medieval drought. *The Holocene* **16**: 159–171.

Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1370.

Holmgren, K., Moberg, A., Svanered, O., and Tyson, P.D. 2001. A preliminary 3000-year regional temperature reconstruction for South Africa. *South African Journal of Science* **97**: 49–51.

Johnson, T.C., Barry, S.L., Chan, Y., and Wilkinson, P. 2001. Decadal record of climate variability spanning the past 700 years in the Southern Tropics of East Africa. *Geology* **29**: 83–86.

Karlén, W., Fastook, J.L., Holmgren, K., Malmstrom, M., Matthews, J.A., Odada, E., Risberg, J., Rosqvist, G., Sandgren, P., Shemesh, A., and Westerberg, L.O. 1999. Glacier Fluctuations on Mount Kenya since ~6000 cal. years BP: implications for Holocene climatic change in Africa. *Ambio* **28**: 409–418.

Mensing, S.A., Benson, L.V., Kashgarian, M., and Lund, S. 2004. A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. *Quaternary Research* **62**: 29–38.

Owen, R.B. and Crossley, R. 1990. Recent sedimentation in Lakes Chilwa and Chiuata, Malawi. *Palaeoecology of Africa* **20**: 109–117.

Owen, R.B., Crossley, R., Johnson, T.C., Tweddle, D., Kornfield, I., Davison, S., Eccles, D.H., and Engstrom, D.E. 1990. Major low levels of Lake Malawi and their implications for speciation rates in Cichlid fishes. *Proceedings of the Royal Society of London Series B* **240**: 519–553.

Proctor, C.J., Baker, A., Barnes, W.L., and Gilmour, M.A. 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Rein, B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

Russell, J.M. and Johnson, T.C. 2005a. A high-resolution geochemical record from Lake Edward, Uganda Congo and the timing and causes of tropical African drought during the late Holocene. *Quaternary Science Reviews* **24**: 1375–1389.

Russell, J.M and Johnson, T.C. 2005b. Late Holocene climate change in the North Atlantic and equatorial Africa: Millennial-scale ITCZ migration. *Geophysical Research Letters* **32**: 10.1029/2005GL023295.

Russell, J.M. and Johnson, T.C. 2007. Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño-Southern Oscillation variability. *Geology* **35**: 21–24.

Russell, J.M., Johnson, T.C., and Talbot, M.R. 2003. A 725-year cycle in the Indian and African monsoons. *Geology* **31**: 677–680.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for Medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schussler, M., and Beer, J. 2004. Unusual activity of the sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.

Springer, G.S., Rowe, H.D., Hardt, B., Edwards, R.L., and Cheng, H. 2008. Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America. *Geophysical Research Letters* **35**: 10.1029/2008GL034971.

Stager, J.C., Ryves, D., Cumming, B.F., Meeker, L.D., and Beer, J. 2005. Solar variability and the levels of Lake Victoria, East Africa, during the last millennium. *Journal of Paleolimnology* **33**: 243–251.

Staubwasser, M., Sirocko, F., Grootes, P., and Segl, M. 2003. Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophysical Research Letters* **30**: 10.1029/2002GL016822.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during medieval time. *Nature* **369**: 546–549.

Stuiver, M. and Braziunas, T.F. 1993. Sun, ocean climate and atmospheric ^{14}CO2: An evaluation of causal and spectral relationships. *The Holocene* **3**: 289–305.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.N., Mikhalenko, V.N., Hardy, D.R., and Beer, J. 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. *Science* **298**: 589–593.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North

Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* **324**: 78–80.

Verschuren, D. 2004. Decadal and century-scale climate variability in tropical Africa during the past 2000 years. In: Battarbee, R.W., Gasse, F. and Stickley, C.E. (Eds.) *Past Climate Variability Through Europe and Africa*. Springer, Dordrecht, The Netherlands, pp.139–158.

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

Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E., and Sawada, M.C. 2002. Widespread evidence of 1500 yr climate variability in North America during the past 14,000 yr. *Geology* **30**: 455–458.

von Rad, U., *et al*. 1999. A 5000-yr record of climate changes in varved sediments from the oxygen minimum zone off Pakistan, northeastern Arabian Sea. *Quaternary Research* **51**: 39–53.

Wang, L., *et al*. 1999. East Asian monsoon climate during the late Pleistocene: High resolution sediment records from the South China Sea. *Marine Geology* **156**: 245–284.

Willard, D.A., Bernhardt, C.E., Korejwo, D.A., and Meyers, S.R. 2005. Impact of millennial-scale Holocene climate variability on eastern North American terrestrial ecosystems: Pollen-based climatic reconstruction. *Global and Planetary Change* **47**: 17–35.

Yu, Z. and Ito, E. 1999. Possible solar forcing of century-scale drought frequency in the northern Great Plains. *Geology* **27**: 263–266.

3.5.2 Floods

The IPCC claims floods will become more variable and extreme as a result of CO_2-induced global warming. In Chapter 7 of this report, addressing extreme weather, we report peer-reviewed research showing modern flood frequency and severity fall well within the range of natural variability. Here we limit our examination once again to the issue of attribution, specifically investigating the influence of the Sun on floods.

We begin by reviewing what is known about the relationship of extreme weather events to climate in Europe during the Holocene. According to Starkel (2002), in general, more extreme fluvial activity, of both the erosional and depositional type, is associated with cooler climates. "Continuous rains and high-intensity downpours," writes Starkel, were most common during the Little Ice Age. Such "flood phases," the researcher reports, "were periods of very unstable weather and frequent extremes of various kinds." Starkel also notes "most of the phases of high frequency of extreme events during the Holocene coincide with the periods of declined solar activity."

In 2010, Markus Czymzik and colleagues published an important article on flooding in the journal of *Water Resources Research* (Czymik *et al.* 2010). The German and French scientists present the flood frequency development of Lake Ammersee (Bavaria's third largest lake) for the past 450 years. They observed an excellent correlation with solar activity as depicted in Figure 3.5.2.1. When solar activity was weak, flooding increased at Lake Ammersee. This relationship also was demonstrated in a February 2013 paper in *Quaternary Science Reviews* (Czymik *et al.* 2013).

Noren *et al*. (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km^2 region in Vermont and eastern New York (USA), after which several techniques were used to identify and date terrigenous in-wash layers depicting the frequency of storm-related floods. The analysis showed "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." Four major storminess peaks were identified, approximately 2.6, 5.8, 9.1, and 11.9 kyr ago, with the most recent upswing in storminess beginning "at about 600 yr BP [before present], coincident with the beginning of the Little Ice Age." Noren *et al.* state the pattern they observed "is consistent with long-term changes in the average sign of the Arctic Oscillation [AO]," further suggesting "changes in the AO, perhaps modulated by solar forcing, may explain a significant portion of Holocene climate variability in the North Atlantic region."

Schimmelmann *et al.* (2003) identified conspicuous gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, which they accurately dated by varve-counting. Analysis of the record revealed six prominent flood events occurring at approximately AD 212, 440, 603, 1029, 1418, and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200, and 1800. They further note "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells"; "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)"; and "the flood of ~AD 1418

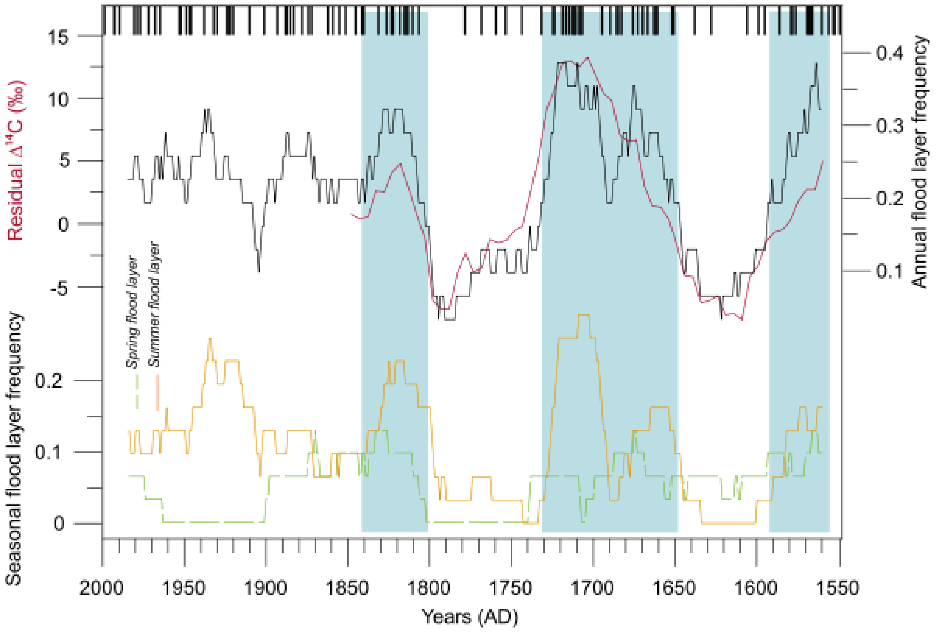

Figure 3.5.2.1. Flooding frequency of the Lake Ammersee region (bottom) and solar activity (above). Phases of minimal solar activity are shown with a blue shaded background. Whenever the sun was weak (high ^{14}C values, peak) flooding was more frequent. Reprinted with permission from Cyzmzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., and Brauer, A. 2010. A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 379-395, 10.1029/ 2009WR008360.

occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al*., 1997; Meeker and Mayewski, 2002)."

Schimmelmann *et al.* also note "the quasi-periodicity of ~200 years for southern California floods matches the ~200-year periodicities found in a variety of high-resolution palaeoclimate archives and, more importantly, a *c*.208-year cycle of solar activity and inferred changes in atmospheric circulation." They "hypothesize that solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years" and "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century."

References

Cyzmzik, M., Brauer, A., Dulski, P., Plessen, B., Naumann, R., von Grafenstein, U., and Scheffler, R. 2013. Orbital and solar forcing of shifts in Mid- to Late Holocene flood intensity from varved sediments of pre-alpine Lake Ammersee (southern Germany). *Quaternary Science Reviews* **61**: 96–110.

Cyzmzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., and Brauer, A. 2010. A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 379-395, 10.1029/ 2009WR008360.

Kennett, D.J. and Kennett, J.P. 2000. Competitive and cooperative responses to climatic instability in coastal southern California. *American Antiquity* **65**: 379–395.

Kreutz, K.J., Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., and Pittalwala, I.I. 1997. Bipolar changes in atmospheric circulation during the Little Ice Age. *Science* **277**: 1294–1296.

Meeker, L.D. and Mayewski, P.A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* **12**: 257–266.

Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., and Southon, J. 2002. Millennial-scale storminess variability in the northeastern Unites States during the Holocene epoch. *Nature* **419**: 821–824.

Schimmelmann, A., Lange, C.B., and Meggers, B.J. 2003.

Palaeoclimatic and archaeological evidence for a 200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. *The Holocene* **13**: 763–778.

Starkel, L. 2002. Change in the frequency of extreme events as the indicator of climatic change in the Holocene (in fluvial systems). *Quaternary International* **91**: 25–32.

3.5.3 Monsoons

The IPCC's computer models fail to predict variability in monsoon weather, at least partly because they underestimate the Sun's role.

The Indian Summer Monsoon (ISM) and its associated local and regional patterns of rainfalls are among the most notoriously complex expressions of the tropical Earth's coupled land, ocean, and atmosphere system. The densely populated countries of South Asia depend critically on the rain water brought on by the ISM during the four summer months from June to September, which is why scientists are keenly interested in understanding the underlying factors responsible for the climatological and anomalous variations of the ISM rainfalls. They have identified a host of factors related to the ISM, from the quasi-biennial oscillation of the equatorial stratospheric winds, ENSO, Eurasian snow cover, conditions of the Indo-Pacific warm pool and Indian subcontinent, and sunspot activity. The pursuit of how the Sun's magnetic activity may modulate the ISM rainfall has been filled with many false starts and promises.

Figure 3.5.3.1 shows the surprising correlations between the All-India and Konkan-Goa regional rainfalls and the new solar forcing index of the derivative of the Total Solar Irradiance (TSI) reported in Agnihotri *et al.* (2011).

Noting many of the weaknesses in previous solar-ISM studies that adopted sunspot numbers or the 10.7 cm solar radio radiation flux, Agnihotri *et al.* (2011) adopt the time-derivative of TSI as a more relevant physical parameter for a better exploration of how the intrinsic solar radiative forcing of the Sun can modulate the ISM rainfall on multidecadal timescales. Van Loon and Meehl (2012) added further insights by arguing for the use of sunspot peaks as another useful metric for a physical investigation of solar-ISM relationship.

The results shown in Figure 3.5.3.1 suggest more severe drought conditions generally prevail during periods of steadily falling TSI or less solar radiation energy added to the Earth system. Periods of positive TSI derivative correspond to periods of anomalous excess of ISM rainfall, although the TSI derivative-rainfall relationship is clearly nonlinear and not fully symmetrical for solar-forcing-induced wet-dry oscillations and transitions.

Figure 3.5.3.2 adds more confidence to the empirical correlation of solar modulation of instrumental ISM rainfall shown in Figure 3.5.3.1 by extending the correlation back to 1700 AD, an additional 150 years of data record. Agnihotri *et al.* (2011) adopted the high-quality rainfall proxy data set obtained from the speleothem $\delta^{18}O$ data from Akalagavi cave located in the hills of the western Ghats mountain range in the southwestern state of Karnataka.

Figure 3.5.3.3 reveals a social dimension to the negative TSI derivative-related dry periods, severe drought, and even major famine (death toll greater than 1 million people) events recorded in all three data sets from instrumental, historical, and proxy records. The statistics from Figure 3.5.3.3 show four of seven major famines recorded in Indian subcontinent history fall near negative TSI derivatives. For example, the "terrible" famine of 1876–1879 that killed an estimated 10 million people (the death was not strictly from starvation alone; outbreaks of cholera were also a known factor) spread across nearly the whole of southern, western, and northern India and was associated with the most negative TSI derivative values constructed. The TSI derivative proxy is also able to pick up the famine events of 1896–1897 and 1899–1902 in which the estimated death tolls ranged from 8.4 to 19 million.

Agnihotri *et al.* (2011) attempted to explain the empirical correlations determined from real-world data (instrumental and proxy) by suggesting the differential addition or subtraction of solar energy to relatively cloud-free regions in the southern Indian ocean "would probably cause warm-pool sea surface conditions and atmospheric convective activity to vary in synchrony with the observed large-scale changes in the summer monsoonal circulation and rainfall in the Indian subcontinent." A positive (negative) TSI derivative phase corresponded to both enhanced (reduced) surface evaporation and an overall increase (decrease) in convective velocity, which in turns leads to the enhanced (reduced) southwest monsoonal circulation and increased (decreased) All-India and Konkan-Goa rainfalls, as observed in Figures 3.5.3.2 and 3.5.3.3.

Neff *et al.* (2001) investigated the relationship between a ^{14}C tree-ring record and a $\delta^{18}O$ proxy

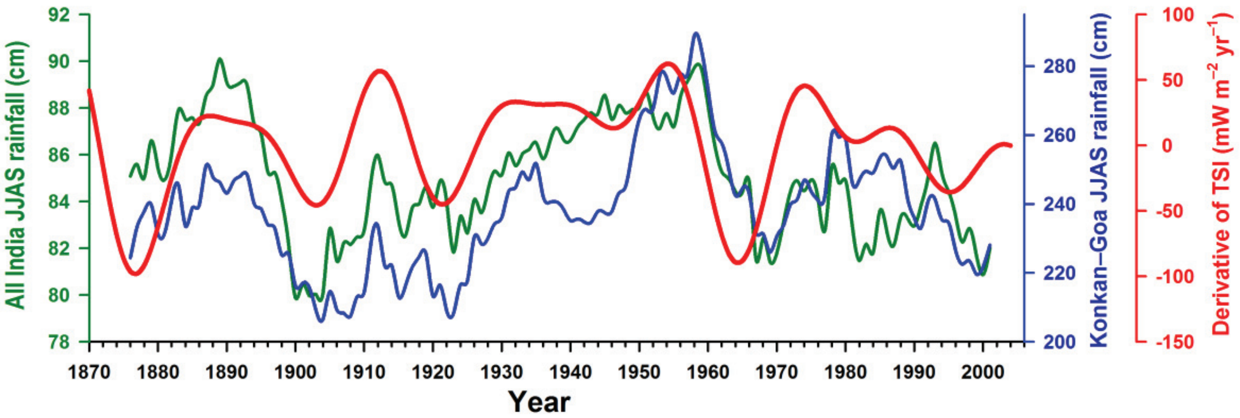

Figure 3.5.3.1. The All Indian Monsoon and Konkan-Goa Regional Monsoon rainfalls are correlated with the temporal derivative of the TSI offering new insights into a plausible solar modulation of the Indian summer monsoon rainfall variability on a multidecadal timescale. Reprinted with permission from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1980–1987.

record of monsoon rainfall intensity for the period 9,600–6,100 years before present, as recorded in calcite δ^{18}O data obtained from a stalagmite in northern Oman. The authors found the correlation between the two data sets to be "extremely strong," and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the δ^{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 tree-ring records are generally attributed to variations in solar activity and intensity, and because this particular ^{14}C record was strongly correlated with the δ^{18}O record as well as the closely corresponding results of the spectral analyses, the authors conclude there is "solid evidence" that both signals (the ^{14}C and δ^{18}O records) are responding to solar forcing.

Similar findings were reported by Lim *et al.* (2005), who examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, creating a 6,500-year proxy record of major Asian dust events produced by northwesterly winter monsoonal winds that carry dust from the inner part of China all the way to Korea and the East China Sea. The Asian dust time series was found to contain both millennial- and centennial-scale periodicities; cross-spectral analysis between the EQC and a solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the researchers to conclude centennial-scale periodicities in the EQC could be ascribed primarily to fluctuations in solar activity.

Ji *et al*. (2005) used reflectance spectroscopy on a sediment core taken from Qinghai Lake in the northeastern part of the Qinghai-Tibet Plateau to construct a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. Monsoonal moisture since the late glacial period was shown to be subject to "continual and cyclic variations," including the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age, which lasted from 2,100 to 1,800 yr BP and 780 to 400 yr BP, respectively. Sandwiched between them was the warmer and wetter Medieval Warm Period, while preceding the DACP was the Roman Warm Period. Time series analysis of the sediment record revealed statistically significant periodicities (above the 95 percent level) of 123, 163, 200, and 293 years. The third of these periodicities corresponds well with the de Vries or Suess solar cycle, suggesting cyclical changes in solar activity are important triggers for some of the cyclical changes in monsoon moisture at Qinghai Lake.

Citing studies that suggest the Indian summer monsoon may be sensitive to changes in solar forcing of as little as 0.25 percent (Overpeck *et al*., 1996; Neff *et al*., 2001; Fleitmann *et al*., 2003), Gupta *et al.* (2005) compared trends in the Indian summer monsoon with trends in solar activity across the Holocene. Temporal trends in the Indian summer

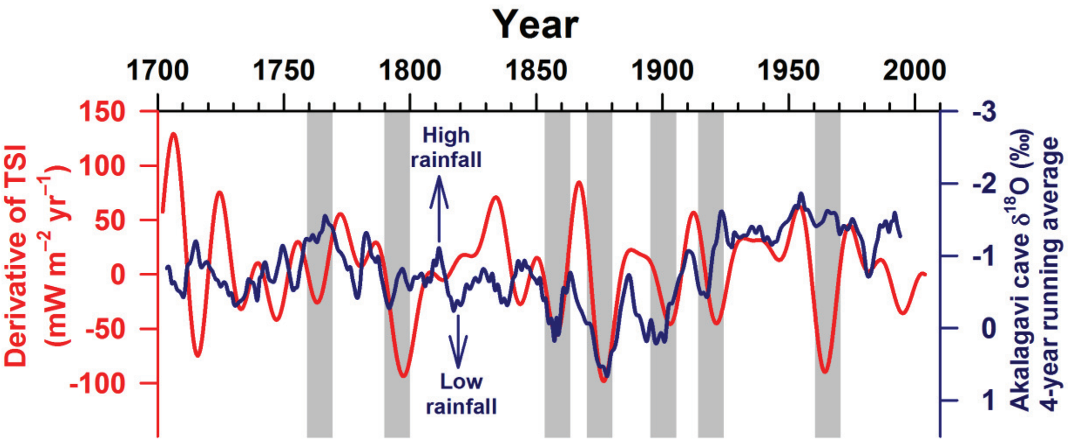

Figure 3.5.3.2. The solar modulation of the Indian summer monsoon rainfall variability on multidecadal timescale relation shown in Figure 3.5.3.1 above can be extended back to about 1700 AD using the rainfall proxy from Akalagavi Cave (located in southwestern India in the state of Karnataka) speleothem δ^{18}O data series. Adapted from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1980–1987.

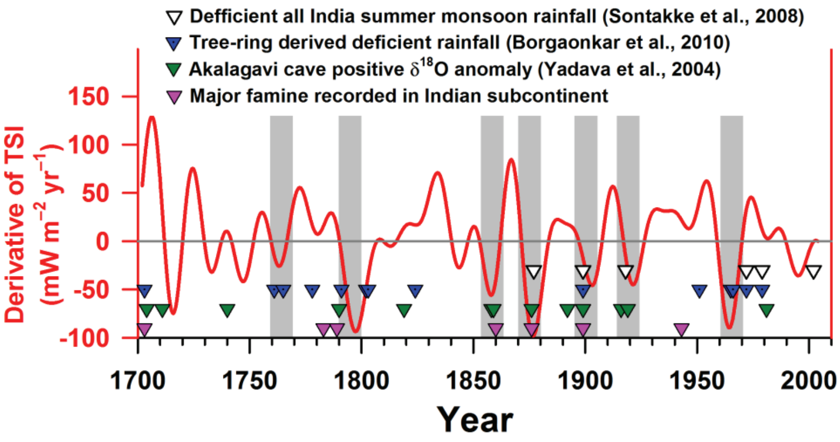

Figure 3.5.3.3. Major drought events from both instrumental and proxy datasets (both tree-ring and speleothem records) as well as major historical famine (death toll exceeding 1 million people) correspond roughly with intervals with low or most negative TSI derivatives (marked by gray vertical bars). Also adapted from Agnihotri *et al*. (2011).

monsoon were inferred from relative abundances of fossil shells of the planktic foraminifer *Globigerina bulloides* in sediments of the Oman margin, while temporal trends in solar variability were inferred from relative abundances of ^{14}C, ^{10}Be and haematite-stained grains.

Spectral analyses of the data sets revealed statistically significant periodicities in the *G. bulloides* time series centered at 1550, 152, 137, 114, 101, 89, 83, and 79 years; all but the first of these periodicities closely matched periodicities of sunspot numbers centered at 150, 132, 117, 104, 87, 82, and 75 years. Gupta *et al.* conclude this close correspondence provides strong evidence for a "century-scale relation between solar and summer monsoon variability." In addition, they report intervals of monsoon minima correspond to intervals of low sunspot numbers, increased production rates of the cosmogenic nuclides ^{14}C and ^{10}Be, and increased advection of drift ice in the North Atlantic, such that over the past 11,100 years "almost every multi-decadal to centennial scale decrease in summer monsoon strength is tied to a distinct interval of reduced solar output," and nearly every increase "coincides with elevated solar output," including a stronger monsoon (high solar activity) during the Medieval Warm Period and a weaker monsoon (low solar activity) during the Little Ice Age.

Gupta *et al.* consider the presence of the 1,550-year cycle in the Indian monsoon data to be "remarkable," as this cycle has been identified in numerous climate records of both the Holocene and the last glacial epoch (including Dansgaard/Oeschger cycles in the North Atlantic), strengthening the case for a Sun-monsoon-North Atlantic link. The researchers say they are "convinced" there is a direct solar influence on the Indian summer monsoon in which small changes in solar output bring about pronounced changes in tropical climate.

Khare and Nigam (2006) examined variations in angular-asymmetrical forms of benthic foraminifera and planktonic foraminiferal populations in a shallow-water sediment core obtained off Kawar (14°49'43"N, 73°59'37"E) on the central west coast of India, which receives heavy river discharge during the southwest monsoon season (June to September) from the Kali and Gangavali rivers. Down-core plots of the data showed three major troughs separated by intervening peaks, and "since angular-asymmetrical forms and planktonic foraminiferal population are directly proportional to salinity fluctuations," according to Khare and Nigam, "the troughs ... suggest low salinity (increased river discharge and thus more rainfall)," and "these wet phases are alternated by dry conditions." They further report the dry episodes of higher salinity occurred in AD 1320–1355, 1445–1535, and 1625–1660; the wet phases were centered at approximately AD 1410, 1590, and 1750, close to the ending of the sunspot minima of the Wolf Minima (AD 1280–1340), the Sporer Minima (AD 1420–1540), and the Maunder Minima (AD 1650–1710), respectively.

Although Khare and Nigam state "providing a causal mechanism is beyond the scope of the present study," they note "the occurrence of periods of enhanced monsoonal precipitation slightly after the termination of the Wolf, Sporer and Maunder minima periods (less Sun activity) and concomitant temperature changes could be a matter of further intense research." The correspondences seem to be more than merely coincidental, especially when the inferences of the two researchers are said to be "in agreement with the findings of earlier workers, who reported high lake levels from Mono Lake and Chad Lake in the vicinity of solar minima," as well as the Nile river in Africa, which "witnessed high level at around AD 1750 and AD 1575."

Tiwari *et al.* (2005) conducted a high-resolution (~50 years) oxygen isotope analysis of three species of planktonic foraminifera (*Globigerinoides ruber*, *Gs. Sacculifer,* and *Globarotalia menardii*) contained in a sediment core extracted from the eastern continental margin (12.6°N, 74.3°E) of the Arabian Sea, covering the past 13,000 years. Data for the final 1,200 years of this period were compared with the reconstructed total solar irradiance (TSI) record developed by Bard *et al.* (2000), based on fluctuations of ^{14}C and ^{10}Be production rates obtained from tree rings and polar ice sheets.

The researchers found the Asian Southwest Monsoon (SWM) "follows a dominant quasi periodicity of ~200 years, which is similar to that of the 200-year Suess solar cycle (Usokin *et al*., 2003)." This finding indicates, in their words, "that SWM intensity on a centennial scale is governed by variation in TSI," which "reinforces the earlier findings of Agnihotri *et al.* (2002) from elsewhere in the Arabian Sea."

In considering the SWM/TSI relationship, the five researchers note "variations in TSI (~0.2%) seem to be too small to perturb the SWM, unless assisted by some internal amplification mechanism with positive feedback," and they discuss two possible mechanisms. The first "involves heating of the Earth's stratosphere by increased absorption of solar ultraviolet (UV) radiation by ozone during periods of enhanced solar activity (Schneider, 2005)." According to this scenario, more UV reception leads to more ozone production in the stratosphere, which leads to more heat being transferred to the troposphere, which leads to enhanced evaporation from the oceans, which finally enhances monsoon winds and precipitation. The second mechanism, as they describe it, is that "during periods of higher solar activity, the flux of galactic cosmic rays to the Earth is reduced, providing less cloud condensation nuclei, resulting in less cloudiness (Schneider, 2005; Friis-Christensen and Svensmark, 1997)," which then allows for "extra heating of the troposphere" that "increases the evaporation from the oceans."

Dykoski *et al.* (2005) obtained high-resolution records of stable oxygen and carbon isotope ratios from a stalagmite recovered from Dongge Cave in southern China and developed a proxy history of Asian monsoon variability over the past 16,000 years. They discovered numerous centennial- and multidecadal-scale oscillations in the record up to half the amplitude of interstadial events of the last glacial age, indicating "significant climate variability characterizes the Holocene." Spectral analysis of $\delta^{14}C$ data revealed significant peaks at solar periodicities of 208, 86, and 11 years, which they say is "clear evidence that some of the variability in the monsoon can be explained by solar variability."

Building on this work and that of Yuan *et al.* (2004), Wang *et al.* (2005) developed a shorter (9,000-year) but higher-resolution (4.5-year) absolute-dated $\delta^{18}O$ monsoon record for the same location, which they compared with atmospheric ^{14}C data and climate records from lands surrounding the North Atlantic Ocean. Their monsoon record broadly followed summer insolation but was punctuated by eight significantly weaker monsoon periods lasting from one to five centuries, most of which coincided with North Atlantic ice-rafting events. In addition, they found "cross-correlation of the decadal- to centennial-scale monsoon record with the atmospheric ^{14}C record shows that some, but not all, of the monsoon variability at these frequencies results from changes in solar output," similar to "the relation observed in the record from a southern Oman stalagmite (Fleitmann *et al*., 2003)."

In a news item by Kerr (2005) accompanying the report of Wang *et al*., one of the report's authors (Hai Cheng of the University of Minnesota) was quoted as saying their study suggests "the intensity of the summer [East Asian] monsoon is affected by solar activity." Dominik Fleitman, who worked with the Oman stalagmite, also said "the correlation is very strong," stating it is probably the best monsoon record he had seen, "even better than ours." Gerald North of Texas A & M University, whom Kerr described as a "longtime doubter," admitted he found the monsoon's solar connection "very hard to refute," although he stated "the big mystery is that the solar signal should be too small to trigger anything."

Porter and Weijian (2006) used 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers "represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation," while "brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate."

The most recent of the episodic cold periods, which Porter and Weijian identify as the Little Ice Age, began about AD 1370, and the preceding cold period ended somewhere in the vicinity of AD 810. Consequently, their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. They also report the climatic variations they discovered "correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water." This correlation implies solar forcing (see Bond *et al*., 2001) as the most likely cause of the alternating multicentury mild/moist and cold/dry periods of North-Central China. Porter and Weijian's work thus helps establish the global extent of the Medieval Warm Period as well as its likely solar origin.

A 2009 study provides further evidence of relationships between solar controls and the Asian Monsoon. Based on carbonate percentages and ostracod abundances found in sediment cores they extracted from Hurleg Lake in the arid Qaidam Basin of the Northeast Tibetan Plateau, Zhao *et al*. (2009) developed a history of precipitation-driven changes in lake level over the past 1,700 years, which they compared with a contemporaneous history of tree-ring-derived precipitation over surrounding mountain-ous terrain as well as with changes in solar activity manifest in solar proxy residual $\Delta^{14}C$ data. The authors discovered "carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the last 1000 years," with the moisture pattern in the Qaidam Basin being "in opposite relation to tree-ring-based monsoon precipitations in the surrounding mountains, suggesting that topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region." In addition, they found cross-spectral analysis between their moisture proxies and the solar activity proxy "shows high coherence at the ~200-year periodicity which is similar to Chinese monsoon intensity records, implying the possible solar forcing of moisture oscillations in the NE Tibetan Plateau."

Zhao *et al*.'s work provides another example of cyclical solar activity controlling the cyclical nature of precipitation variations, wherein "higher solar output corresponds to a stronger monsoon, which intensifies the uplift of air mass on the high Tibetan Plateau and strengthens the subsidence of air mass over the Qaidam Basin," whereas "the reverse is true during the period of lower solar output," so that "high solar activity is correlated with dry climate in the Qaidam Basin and increased precipitation in monsoonal areas."

At this juncture, insights from the climate modeling effort can be instructive. In their study of centennial variations of global monsoon precipitation in the last millennium, Liu *et al.* (2009) called attention to the nonlinear responses in the climate model for a 0.2% increase in external solar forcing in triggering a 0.9% change in global monsoon precipitation, or an amplification factor of 4 to 5. Liu *et al.* explained the physical relation as follows:

> We argue that the effective radiative forcing-induced land-ocean thermal contrast causes an initial increase in monsoon precipitation. This initial increase is further reinforced by the increase in moisture supply because the warming induced by effective radiative heating tends to increase atmospheric moisture content. The increase in moisture supply can induce a positive feedback between the latent heat release (in precipitation) and monsoon flow convergence, thus further amplify the latent heat release, which may ultimately amplify the atmospheric circulation response. Therefore, the humidity feedback is a key amplifier linking solar irradiance and monsoon." (p. 2368)

In a study of the North American monsoon, Asmerom *et al.* (2007) developed a high-resolution climate proxy for the southwest United States in the form of δ^{18}O variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw δ^{18}O data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." They report cross-spectral analysis of the Δ^{14}C and δ^{18}O data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon); this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

References

Agnihotri, R., Dutta, K., Bhushan, R., and Somayajulu, B.L.K. 2002. Evidence for solar forcing on the Indian monsoon during the last millennium. *Earth and Planetary Science Letters* **198**: 521–527.

Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1980–1987.

Asmerom, Y., Polyak, V., Burns, S., and Rassmussen, J. 2007. Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology* **35**: 1–4.

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus B* **52**: 985–992.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D., Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., and Revenaugh, J. 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth and Planetary Science Letters* **233**: 71–86.

Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter, A. 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* **300**: 1737–1739.

Friis-Christensen, E. and Svensmark, H. 1997. What do we really know about the Sun-climate connection? *Advances in Space Research* **20**: 913–921.

Gupta, A.K., Das, M., and Anderson, D.M. 2005. Solar influence on the Indian summer monsoon during the Holocene. *Geophysical Research Letters* **32**: 10.1029/2005GL022685.

Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L., and Liu, X. 2005. Asian monsoon oscillations in the northeastern Qinghai-Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters* **233**: 61–70.

Kerr, R.A. 2005. Changes in the Sun may sway the tropical monsoon. *Science* **308**: 787.

Khare, N. and Nigam, R. 2006. Can the possibility of some linkage of monsoonal precipitation with solar variability be ignored? Indications from foraminiferal proxy records. *Current Science* **90**: 1685–1688.

Lim, J., Matsumoto, E., and Kitagawa, H. 2005. Eolian quartz flux variations in Cheju Island, Korea, during the last 6500 yr and a possible Sun-monsoon linkage. *Quaternary Research* **64**: 12–20.

Liu, J., Wang, B., Ding, Q., Kuang, X., Soon, W., and Zorita, E. 2009. Centennial variations of the global monsoon precipitation in the last millennium: Results from ECHO-G model. *Journal of Climate* **22**: 2356–2371.

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.

Overpeck, J.T., Anderson, D.M., Trumbore, S., and Prell, W.L. 1996. The southwest monsoon over the last 18,000 years. *Climate Dynamics* **12**: 213–225.

Porter, S.C. and Weijian, Z. 2006. Synchronism of Holocene East Asian monsoon variations and North Atlantic drift-ice tracers. *Quaternary Research* **65**: 443–449.

Schneider, D. 2005. Living in sunny times. *American Scientist* **93**: 22–24.

Stuiver, M. and Braziunas, T.F. 1993. Sun, ocean climate and atmospheric $^{14}CO_2$: An evaluation of causal and spectral relationships. *The Holocene* **3**: 289–305.

Tiwari, M., Ramesh, R., Somayajulu, B.L.K., Jull, A.J.T., and Burr, G.S. 2005. Solar control of southwest monsoon on centennial timescales. *Current Science* **89**: 1583–1588.

Usoskin, I.G. and Mursula, K. 2003. Long-term solar cycle evolution: Review of recent developments. *Solar Physics* **218**: 319–343.

van Loon, H. and Meehl, G.A. 2012. The Indian summer monsoon during peaks in the 11 year sunspot cycle. *Geophysical Research Letters* **39**: 10.1029/2012GL051977.

Wang, Y., Cheng, H., Edwards, R.L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M.J., Dykoski, C.A., and Li, X. 2005. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science* **308**: 854–857.

Yuan, D., Cheng, H., Edwards, R.L., Dykoski, C.A., Kelly, M.J., Zhang, M., Qing, J., Lin, Y., Wang, Y., Wu, J., Dorale, J.A., An, Z., and Cai, Y. 2004. Timing, duration, and transitions of the last interglacial Asian monsoon. *Science* **304**: 575–578.

Zhao, C., Yu, Z., Zhao, Y., and Ito, E. 2009. Possible orographic and solar controls of Late Holocene centennial-scale moisture oscillations in the northeastern Tibetan Plateau. *Geophysical Research Letters* **36**: 10.1029/2009GL040951.

3.5.4 Streamflow

Streamflow is a climate variable related to precipitation, droughts, and floods. The studies reviewed here consider whether a significant solar influence on this variable.

Pederson *et al*. (2001) used tree-ring chronologies to reconstruct annual precipitation and streamflow histories in northeastern Mongolia over the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods revealed “variations over the recent period of instrumental data are not unusual relative to the prior record.” The authors say the reconstructions “appear to show more frequent extended wet periods in more recent decades,” but they note this observation “does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models.” The researchers also observe spectral analysis of the data revealed significant periodicities around 12 and 20–24 years, suggesting “possible evidence for solar influences in these reconstructions for northeastern Mongolia.”

In Western Europe, several researchers have studied precipitation histories of regions along the Danube River and their effects on river discharge, with some studies suggesting an anthropogenic signal present in the latter decades of the twentieth century is responsible for that period’s drier conditions. Ducic (2005) analyzed observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He found the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was nearly equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950); the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. The discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be “completely inside the limits of the whole series" and only slightly (38 m^3s^{-1} or 0.7 percent) less than the 260-year mean of 5356 m^3s^{-1}. In conclusion, Ducic states "modern discharge fluctuations do not point to [a] dominant anthropogenic influence"; further analysis suggests the detected cyclicity in the record may "point to the domination of the influence of solar activity."

Kondrashov *et al*. (2005) applied advanced spectral methods to fill in data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels on the Nile over the 1,300-year period AD 622 to 1922. They found several statistically significant periodicities, including cycles of 256, 64, 19, 12, 7, 4.2, and 2.2 years. Kondrashov *et al.* state the 4.2- and 2.2-year oscillations are likely the product of El Niño-Southern Oscillation variations, the 7-year cycle may be related to North Atlantic influences, and the longer-period oscillations may be due to solar-related forcings.

Mauas *et al*. (2008) note river streamflows "are excellent climatic indicators," especially in the case of rivers "with continental scale basins" that "smooth out local variations" and can thus "be particularly useful to study global forcing mechanisms." Focusing on South America's Parana River—the world's fifth largest in terms of drainage area and fourth largest with respect to streamflow—Mauas *et al*. analyzed streamflow data collected continuously on a daily basis since 1904. They report the detrended time series of the streamflow data were correlated with the detrended times series of both sunspot number and total solar irradiance, yielding Pearson's correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69, respectively, at "a significance level higher than 99.99% in both cases." This is strong evidence that solar variability, not manmade greenhouse gas emissions, was responsible for variation in Parana River streamflow during the modern industrial era.

A follow-up study by Mauas *et al*. (2011) analyzed river streamflows during the Little Ice Age. The authors write low water levels and low level in the flow of the Pirana River (and others) were found during a time of "unusual" minimum of solar activity, once again affirming the notion that solar activity induces significant variations in streamflow.

References

Ducic, V. 2005. Reconstruction of the Danube discharge on hydrological station Orsova in pre-instrumental period: Possible causes of fluctuations. *Edition Physical Geography of Serbia* **2**: 79–100.

Kondrashov, D., Feliks, Y., and Ghil, M. 2005. Oscillatory modes of extended Nile River records (A.D. 622–1922). *Geophysical Research Letters* **32**: doi:10.1029/2004 GL022156.

Mauas, P.J.D., Flamenco, E., and Buccino, A.P. 2008. Solar forcing of the stream flow of a continental scale South American river. *Physical Review Letters* **101**: 168,501–168,505.

Mauas, P.J.D., Buccino, A.P., and Flamenco, E. 2011. Long-term solar activity influences on South American rivers. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 377–382.

Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. *Journal of Climate* **14**: 872–881.

3.6 Future Influences

Sunspot activity for Cycle 23 (from May 1996 until about 2008–2009) and the relatively slow and muted rising phase of Cycle 24 are unusual. This has heightened interest not only in solar magnetic field data but also more generally in the nature of the solar-climate connection. In concluding this chapter we examine recent research and scientists' thoughts on the potential influence of the Sun on Earth's future climate.

Livingston and Penn (2009) confirm "something is unusual about the current sunspot cycle," specifically "the current solar minimum has been unusually long." They note "with more than 670 days without sunspots through June 2009, the number of spotless days has not been equaled since 1933." In addition, they note, "the solar wind is reported to be in a uniquely low energy state since space measurements began nearly 40 years ago," citing the work of Fisk and Zhao (2009).

In 2006, Livingston and Penn reported the magnetic field strengths of sunspots "were decreasing with time, independent of the sunspot cycle" and "a simple linear extrapolation of those data suggested that sunspots might completely vanish by 2015." With several years' more data in hand, they report in 2009 "the predicted cycle-independent dearth in sunspot numbers has proven accurate," with sunspots still on track potentially to disappear in four to five years. That possibility led the two researchers to wonder openly whether their findings represent "an omen of long-term sunspot decline, analogous to the Maunder Minimum," the period 1645–1715 "when through several 11-year periods the Sun displayed few if any sunspots." They note "models of the Sun's irradiance suggest that the solar energy input to the Earth decreased during that time and that this change in solar activity could explain the low temperatures recorded in Europe during the Little Ice Age (Lean *et al*., 1992)."

The decline of the umbral magnetic field strength noted by Livingston and Penn and shown in Figure 3.6.1 (from Livingston *et al.* 2012, based on measurements for the near-infrared feature at Fe I 1565 nm) is not universally recognized. Pevtsov *et al.* (2011) found the sunspot field strengths (based on measurements for the visible line feature at Fe I 630 nm) tend to rise and wane with solar activity cycle; they do not detect a long-term decline of magnetic field strength. Rezaei *et al.* (2012), using more limited observations of 183 sunspots from the Tenerife Infrared Polarimeter, tend to support Pevtsov *et al*.

Nagovitsyn *et al.* (2012) offered a working explanation of the discrepancies between different observations and interpretations, noting opposing trends and dynamics in the largest and smallest sunspots. They write, "Suppose that during a grand solar minimum (e.g., Maunder minimum) the sunspots do not vanish all together, but only the large sunspots disappear. This change would not require the complete shutdown of the solar dynamo. Only the depth dependence of the dynamo will change, and it would favor the production of small sunspots." They point out "the smallest sunspots are much harder to detect, especially with the visual observations conducted with relatively poor telescopes, which could explain the low sunspot counts during some of the past grand minima."

Nagovitsyn *et al.* also point out, "modern observations suggest that the smaller sunspots are less likely to be associated with flare and coronal mass ejection activity, and thus, the magnetic fields on smaller scales may have a reduced effect on the amount of the magnetic field expelled to the heliosphere. The latter may affect the secondary proxies of the solar activity (e.g., cosmic-ray flux and frequency of aurorae) that are often used as additional identifiers of the Maunder minimum." They conclude, "this possibility that the grand minima in solar activity can be related to changes in size of sunspots produced by the dynamo should be explored further …"

Obridko *et al.* (2012) discussed the unusual sunspot minimum for Cycle 23 and what might be expected for the next several decades. They conclude, "after the high cycles of the twentieth century, the solar activity now turns to an average level [for Cycle 24] (rather than to a low one, as some authors believe), and only by the latter half of [the] twenty-first century we can wait for a great minimum of Dalton's type [i.e., 1790–1820]. The probability of a Maunder's type minimum [i.e., 1645–1715] is minimal."

The direct observations as updated in Livingston *et al.* (2012), however, do not rule out a highly muted future sunspot activity cycle. "By extrapolating our sunspot formation fraction to the predicted peak of Cycle 24 (in mid-2013) the sunspot formation fraction would be approaching 0.5 [i.e., a peak in the smoothed sunspot number of about 66–87 as estimated in Penn and Livingston 2011]," they write. "This suggests a rather small SSN for this cycle, in agreement with some recent Cycle 24 predictions."

Projecting further into the future, Livingston *et al.* note, "And while there is no physical mechanism which suggests that we should extrapolate further, it is fascinating to see that the sunspot formation fraction would be below 0.2 [i.e., a peak in the smoothed sunspot number of about 7–20 for Cycle 25 as estimated in Penn and Livingston 2011] by 2020. This would suggest that although magnetic flux would be erupting at solar surface during Cycle 25, only a small fraction of it would be strong enough to form visible sunspots or pores," as shown in Figure 3.6.2. "Such behavior would be highly unusual," they note, "since such a small solar maximum has not been observed since the Maunder Minimum."

In addition to the direct approach of studying the Sun itself, other researchers study the decadal, multidecadal, centennial, bicentennial, and even millennial periods in available climate and solar records in order to extrapolate solar activity into the future.

Solheim *et al*. (2012) point out Archibald (2008) was the first to recognize previous sunspot cycle length (PSCL) has a predictive power for temperature in the next sunspot cycle, if the raw (unsmoothed) value for the sunspot cycle length (SCL) is used, which Archibald demonstrated with data from de Bilt in the Netherlands; Hanover, New Hampshire, USA; Portland, Maine, USA; Providence, Rhode Island, USA; and Archangel, Russia.

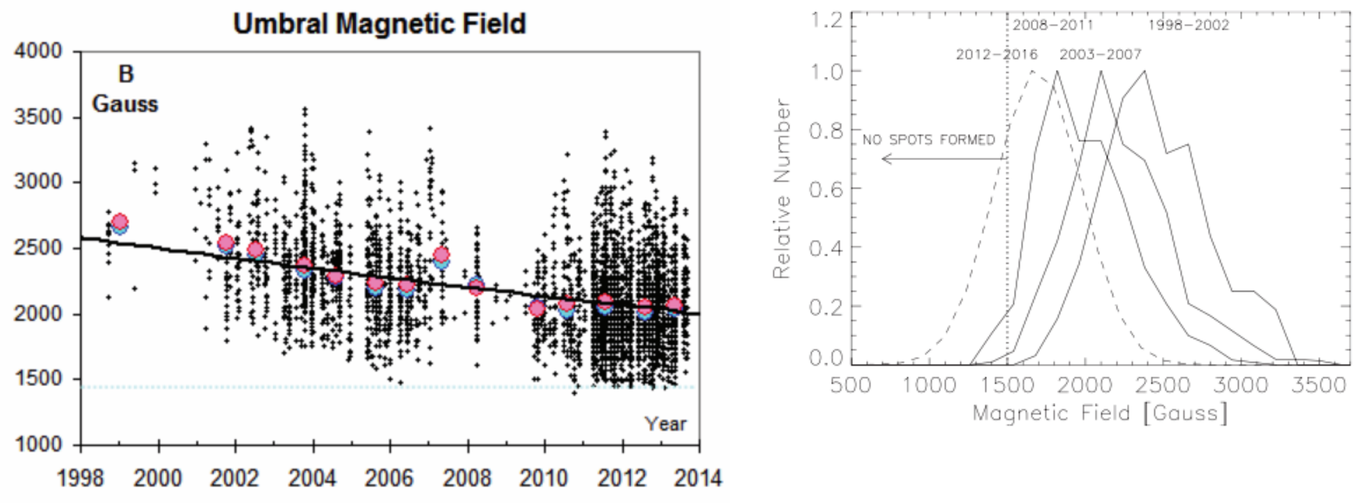

Figure 3.6.1. The measured sunspot umbral magnetic field strength from 1998 until April 2013 (left panel) and the distribution of the magnetic field strength for the same interval and the predicted distribution for 2012-2016 (right panel). It is predicted that a significant fraction of the magnetic fields will be below the threshold of 1500 G for the formation of sunspot. Adapted from Livingston, W., Penn, M.J., and Svalsgaard, L. 2012. Decreasing sunspot magnetic fields explain unique 10.7 cm radio flux. *The Astrophysical Journal Letters* **757**: L8. Left panel updated by Livingston in private correspondence, September 9, 2013.

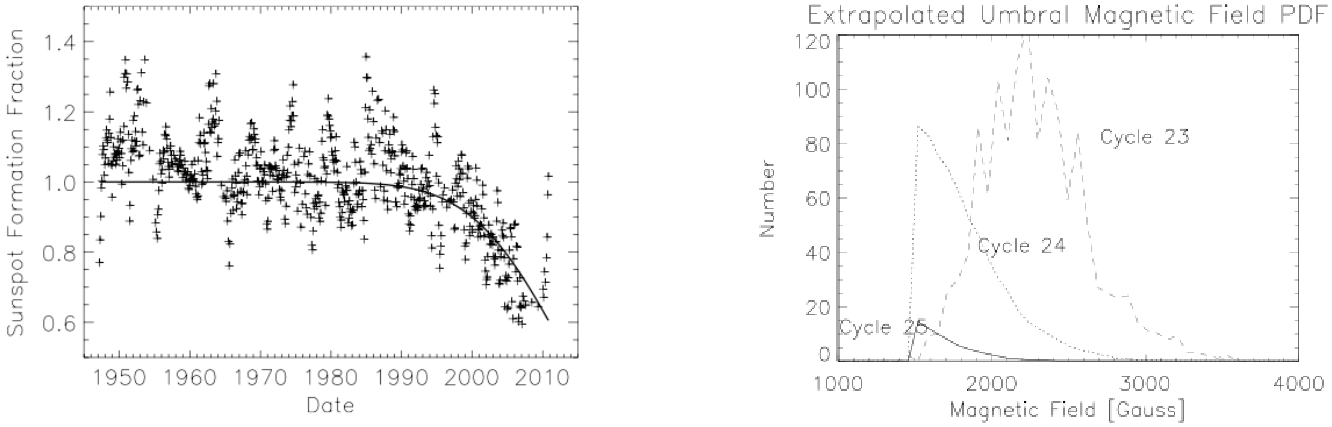

Figure 3.6.2. The history of the fraction of sunspot formation from about 1947 to present (left panel) illustrating the unusual nature of Cycles 23 and 24. The estimated distribution of sunspot magnetic field strengths for Cycle 23 contrasting those extrapolated for Cycles 24 and 25 (right panel). Left panel also adapted from Livingston *et al.* (2012). Right panel adapted from Penn, M.J. and Livingston, W. 2011. Long-term evolution of sunspot magnetic fields. In Choudhary, D.P. and Strassmeier, K.G. (Eds.) IAU Symposium No. 273, *The Physics of Sun and Star Spots*, (Cambridge: Cambridge University Press), pp. 126–133.

Solheim *et al*. further explored this relationship by comparing the raw SCL values and temperatures in the same and next sunspot cycles for a selection of weather stations in Norway and other European locations as well as sites across the North Atlantic region, including Armagh, Archangel, the Faroe Islands, Iceland, Svalbard and Greenland. The stations offered long weather records at places with small populations (to minimize urban heat island effects) in both coastal and inland locations.

The three Norwegian researchers found significant linear relationships between the average air temperature in a solar cycle and the length of the previous solar cycle for 12 of 13 weather stations in Norway and in the North Atlantic, as well as for 60 European stations and for the HadCRUT3N database. For Norway and the other European stations, they found "the solar contribution to the temperature variations in the period investigated is of the order 40%," while "an even higher contribution (63–72%) is found for stations at the Faroe Islands, Iceland and Svalbard," which they note is considerably "higher than the 7% attributed to the Sun for the global temperature rise in AR4 (IPCC, 2007)."

Solheim *et al.* say their findings imply "an annual average temperature drop of 0.9°C in the Northern Hemisphere during solar cycle 24," and "for the measuring stations south of 75°N, the temperature decline is of the order 1.0–1.8°C and may already have started." For Svalbard, they say "a temperature decline of 3.5°C is forecasted in solar cycle 24 for the yearly average temperature," and "an even higher temperature drop is forecasted in the winter months (Solheim *et al.*, 2011)." They caution, "since solar forcing on climate is present on many timescales, we do not claim that our result gives a complete picture of the Sun's forcing on our planet's climate."

Ludecke *et al.* (2013) considered six periodic components with timescales greater than 30 years in the composite of a six-station temperature record from Central Europe since about 1757 AD, creating a very good reconstruction of the original instrumental records. They project a substantial cooling of the Central European temperature in the next one to two decades but caution their result "does not rule out a warming by anthropogenic influences such as an increase of atmospheric CO_2." The authors also note, "while … many indications point to the oscillations as intrinsic dynamics of the Earth, external causes for periodic dynamics cannot be ruled out."

The weak and delayed Cycle 24 surprised a number of solar experts, but not all of them. In 2003, a small group led by Mark Clilverd of the British Antarctic Survey in Cambridge had sensed something was amiss even before there were signs pointing to a slowdown in the Schwabe solar cycles (Clilverd *et al.*, 2003). Clilverd *et al.* produced a solar activity forecast through 2140, which they further refined in 2006 (Clilverd *et al.*, 2006). They predicted a strongly reduced Cycle 24 would mark the start of a solar activity slumber extending until the year 2030, at which time solar activity would pick up and remain at a more elevated level until 2100, after which another pronounced, extended quiet period would ensue. Their forecast was based on a careful analysis of the entire suite of known solar cycles, from the 11-year Schwabe Cycle to the 2,300-year Hallstatt Cycle. By extending these oscillations into the future, they correctly predicted the collapse in solar activity in Cycle 24 that followed a few years later.

In analyzing the global temperature data records (HadCRUT3 and HadCRUT4, respectively) directly, Loehle and Scafetta (2011) and Tung and Zhou (2013) conclude a large fraction of recent observed warming (60 percent over 1970–2000 and 40 percent over the past 50 years) can be accounted for by the natural upswing of the 60-year climatic cycle during its warming phase. Loehle and Scafetta (2011) proffer that "a 21st Century forecast suggests that climate may remain approximately steady until 2030–2040, and may at most warm 0.5–1.0°C by 2100 at the estimated 0.66°C/century anthropogenic warming rate, which is about 3.5 times smaller than the average 2.3°C/century anthropogenic warming rate projected by the IPCC up to the first decades of the 21st century. However, additional multisecular natural cycles may cool the climate further."

In an independent analysis of global temperature data from the Climatic Research Unit at the University of East Anglia and the Berkeley Earth Surface Temperature consortium, Courtillot *et al.* (2013) arrive at a new view of the significance of the ~60 yr oscillation. They interpret the 60-year period found in the global surface temperature records as "a series of ~30-yr long linear segments, with slope breaks (singularities) in ~1904, ~1940, and ~1974 (±3 yr), and a possible recent occurrence at the turn of the 21st century." Courtillot and his colleagues suggest "no further temperature increase, a dominantly negative PDO index and a decreasing AMO index might be expected for the next decade or two."

By extrapolating present solar cycle patterns into the future, several scientists have suggested a planetary cooling may be expected over the next few decades. The Gleissberg and Suess/de Vries cycles will reach their low points between 2020 and 2040 at a level comparable to what was experienced during the Dalton Minimum. At that time, around 1790–1820, global temperatures were nearly 1°C lower than they are today; conservatively, at least half of that cooling was due to a weaker Sun.

Moreover, the Pacific Decadal Oscillation (PDO) is expected to be in a cool phase by 2035, and the Atlantic Multidecadal Oscillation (AMO) will begin to drop around 2020. Such internal climate cycles are generally responsible for about 0.2 to 0.3°C of the temperature dynamic.

By calibrating the natural climate cycles to the documented geological data series of the past, we can project a total cooling contribution from these natural climate forcings of 0.4 to 0.6°C by the year 2035 as compared to today. Such cooling might be masked to some extent by anthropogenic effects, such as greenhouse gases, urbanization, and land-use change. Only time will tell whether such interpolations of future climate are correct, but given the stagnant temperatures experienced over the past decade, the odds may favor the Sun.

References

Archibald, D. 2008. Solar cycle 24: Implications for the United States. International Conference on Climate Change. http://www.davidarchibald.info/.

Clilverd, M.A., Clarke, E., Ulich, T., Rishbeth, H., and Jarvis, M.J. 2006. Predicting Solar Cycle 24 and beyond. *Space Weather* **4**: 1–7.

Clilverd, M.A., Clarke, E., Rishbeth, H., Clark, T.D.G., and Ulich, T. 2003. Solar activity levels in 2100. *Astronomy & Geophysics* **44**: 5.20–5.22.

Courtillot, V., Le Mouel, J.-L., Kossobokov, V., Gibert, D., and Lopes, F. 2013. Multi-decadal trends of global surface temperature: A broken line with alternating ~30 yr linear segments? *Atmospheric and Climate Sciences* **3**: **in press**.

Fisk, L.A. and Zhao, L. 2009. The heliospheric magnetic field and the solar wind during the solar cycle. In: Gopalswamy, N. and Webb, D.F., Eds. *Universal Heliophysical Processes: Proceedings of the International Astronomical Union* **257**: 109–120 (Cambridge University Press, New York, New York, USA).

Lean, J., Skumanich, A., and White, O. 1992. Estimating the Sun's radiative output during the Maunder Minimum. *Geophysical Research Letters* **19**: 1591–1594.

Livingston, W. and Penn, M. 2009. Are sunspots different during this solar minimum? *EOS, Transactions, American Geophysical Union* **90**: 257–258.

Livingston, W., Penn, M.J., and Svalsgaard, L. 2012. Decreasing sunspot magnetic fields explain unique 10.7 cm radio flux. *The Astrophysical Journal Letters* **757**: L8.

Loehle, C. and Scafetta, N. 2011. Climate change attribution using empirical decomposition of climatic data. *The Open Atmospheric Science Journal* **5**: 74–86.

Ludecke, H.-J., Hempelmann, A., and Weiss, C.O. 2013. Multi-periodic climate dynamics: Spectral analysis of long-term instrumental and proxy temperature records. *Climate of the Past* **9**: 447–452.

Nagovitsyn, Yu.A., Pevtsov, A.A., and Livingston, W.C. 2012. On a possible explanation of the long-term decrease in sunspot field strength. *The Astrophysical Journal Letters* **758**: L20.

Obridko, V.N., Nagovitsyn, Yu.A., and Georgieva, K. 2012. The unusual sunspot minimum: Challenge to the solar dynamo theory. In *The Sun: New Challenges*, Proceedings of Symposium 3 of JENAM 2011, Astrophysics and Space Science Proceedings **30:** 1–12 (Springer-Verlag Berlin Heidelberg).

Penn, M.J. and Livingston, W. 2006. Temporal changes in sunspot umbral magnetic fields and temperatures. *The Astrophysical Journal Letters* **649**: L45–L48.

Penn, M.J. and Livingston, W. 2011. Long-term evolution of sunspot magnetic fields. In Choudhary, D.P. and Strassmeier, K.G. (Eds.) IAU Symposium No. 273, *The Physics of Sun and Star Spots*, (Cambridge: Cambridge University Press), pp. 126–133.

Pevtsov, A.A., Nagovitsyn, Yu.A., Tlatov, A.G., and Rybak, A.L. 2011. Long-term trends in sunspot magnetic fields. *The Astrophysical Journal Letters* **742**: L36.

Rezaei, R., Beck, C., and Schmidt, W. 2012. Variation in sunspot properties between 1999 and 2011 as observed with the Tenerife Infrared Polarimeter. *Astronomy & Astrophysics* **541**: A60.

Solheim, J.-E., Stordahl, K., and Humlum, O. 2011. Solar activity and Svalbard temperatures. *Advances in Meteorology* **2011**: 10.1155/2011/543146.

Solheim, J.-E., Stordahl, K., and Humlum, O. 2012. The long sunspot cycle 23 predicts a significant temperature decrease in cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 267–284.

Tung, K.-K. and Zhou, J. 2013. Using data to attribute episodes of warming and cooling instrumental records. *Proceedings of the National Academy of Sciences, USA* **110**: 2058–2063.