6

OBSERVATIONS: EXTREME WEATHER

Introduction

The Intergovernmental Panel on Climate Change (IPCC) claims, in Section 3.8 of the report of Working Group I to the Fourth Assessment Report, that global warming will cause (or already is causing) more extreme weather: droughts, floods, tropical cyclones, storms, and more (IPCC, 2007-I). Chapter 5 of the present report presented extensive evidence that solar variability, not CO_2 concentrations in the air or rising global temperatures (regardless of their cause) is responsible for trends in many of these weather variables. In this chapter we ask if there is evidence that the twentieth century, which the IPCC claims was the warmest century in a millennium, experienced more severe weather than was experienced in previous, cooler periods. We find no support for the IPCC's predictions. In fact, we find more evidence to support the opposite prediction: that weather would be *less* extreme in a warmer world.

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6.1. Droughts

One of the many dangers of global warming, according to the IPCC, is more frequent, more severe, and longer-lasting droughts. In this section, we discuss the findings of scientific papers that compared droughts in the twentieth century with those longer ago, beginning with Africa and then Asia, Europe, and finally North America.

Additional information on this topic, including reviews on drought not discussed here, can be found at http://www.co2science.org/subject/d/subject_d .php under the heading Drought.

6.1.1. Africa

Lau *et al.*, 2006 explored "the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought" in the computer models used by the IPCC for its Fourth Assessment Report. These 19 computer models were "driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions." This work revealed that "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, they report that "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events."

All 19 of the models used in preparing the IPCC's Fourth Assessment Report were unable to adequately simulate the basic characteristics of what Lau *et al.* call one of the past century's "most pronounced signals of climate change." This failure of what the authors call an "ideal test" for evaluating the models' abilities to accurately simulate "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" vividly illustrates the fallibility of computer climate models.

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

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

Looking further back in time, Verschuren *et al*. (2000) developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years, based on level and salinity fluctuations of a small crater-lake in Kenya that were derived from diatom and midge assemblages retrieved from the lake's sediments. Once again, they found that the Little Ice Age was generally wetter than the Current Warm Period; but they identified three intervals of prolonged dryness within the Little Ice Age (1390-1420, 1560-1625, and 1760-1840), and of these "episodes of persistent aridity," as they refer to them, *all* were determined to have been "more severe than any recorded drought of the twentieth century."

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

Last, and going back in time almost 5,500 years, Russell and Johnson (2005) analyzed sediment cores that had been retrieved from Lake Edward—the smallest of the great rift lakes of East Africa, located on the border that separates Uganda and the Democratic Republic of the Congo—to derive a detailed precipitation history for that region. In doing so, they discovered that from the start of the record until about 1,800 years ago, there was a long-term trend toward progressively more arid conditions, after which there followed what they term a "slight trend" toward wetter conditions that has persisted to the present. In addition, superimposed on these long-term trends were major droughts of "at least century-scale duration," centered at approximately 850, 1,500, 2,000, and 4,100 years ago. Consequently, it would not be unnatural for another such drought to grip the region in the not-too-distant future.

In summation, real-world evidence from Africa suggests that the global warming of the past century or so has not led to a greater frequency or greater severity of drought in that part of the world. Indeed, even the continent's worst drought in recorded meteorological history was much milder than droughts that occurred periodically during much colder times.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtafrica.php.

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6.1.2. Asia

Paulsen *et al*. (2003) employed high-resolution stalagmite records of $\delta^{13}C$ and $\delta^{18}O$ from Buddha Cave "to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and twentieth century warming, lending support to the global extent of these events." More specifically, their record begins in the depths of the Dark Ages Cold Period, which ends about AD 965 with the commencement of the Medieval Warm Period. The warming trend continues until approximately AD 1475, whereupon the Little Ice Age sets in. That cold period holds sway until about AD 1825, after which the warming responsible for the Current Warm Period begins.

With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet. It, in turn, was followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Current Warm Period. Paulsen *et al*.'s data also reveal a number of other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture. They attribute most of these higher-frequency cycles to solar phenomena and not CO_2 concentrations in the air. Paulsen *et al.* conclude that the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

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

With respect to moisture and precipitation, Kalugin *et al.* state that the period between 1210 and 1480 was more humid than that of today, while the period between 1480 and 1840 was more arid. In addition, they report three episodes of multi-year drought (1580-1600, 1665-1690, and 1785-1810), which findings are in agreement with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al*., 1996; Panyushkina *et al*., 2000). It is problematic for the IPCC to claim that global warming will lead to more frequent and more severe droughts, as *all* of the major multi-year droughts detected in this study occurred during the cool phase of the 800-year record.

Touchan *et al*. (2003) developed two reconstructions of spring precipitation for southwestern Turkey from tree-ring width measurements, one of them (1776-1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia,* and *Pinus nigra*, and the other one (1339-1998) based on three chronologies of *Juniperus excelsa*. These records, according to them, "show clear evidence of multi-year to decadal variations in spring precipitation." Nevertheless, they report that "dry periods of 1-2 years were well distributed throughout the record" and that the same was largely true of similar wet periods. With respect to more extreme events, the period preceding the Industrial Revolution stood out. They note, for example, that "all of the wettest 5-year periods occurred prior to 1756." Likewise, the longest period of reconstructed spring drought was the four-year period 1476-79, while the single driest spring was 1746. We see no evidence that the past century produced distinctive changes in the nature of drought in this part of Asia.

Cluis and Laberge (2001) analyzed streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any changes in Asian river runoff of the type predicted by the IPCC to lead to more frequent and more severe drought. This study was based on the streamflow histories of 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region." The mean start and end dates of these series were 1936 ± 5 years and 1988 ± 1 year, respectively, representing an approximate half-century time span. In the case of the annual minimum discharges of these rivers, which are the ones associated with drought, 53 percent of them were unchanged over the period of the study; where there were trends, 62 percent of them were upward, indicative of a growing likelihood of both less frequent and less severe drought.

Ducic (2005) analyzed observed and reconstructed discharge rates of the Danube River near Orsova, Serbia, over the period 1731-1990, finding that 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 that the driest decade of the entire 260-year period was 1831-1840. The discharge rate for the last decade of the record (1981-1990), was "completely inside the limits of the whole series," in Ducic's words, and only slightly (0.7 percent) less than the 260-year mean. As a result, Ducic concluded that "modern discharge fluctuations do not point to [a] dominant anthropogenic influence." Ducic's correlative analysis suggests that the detected cyclicity in the record could "point to the domination of the influence of solar activity."

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

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

Sinha *et al*. (2007) derived a nearly annually resolved record of Indian summer monsoon (ISM) rainfall variations for the core monsoon region of India that stretches from AD 600 to 1500 based on a ^{230}Th-dated stalagmite oxygen isotope record from Dandak Cave, which is located at 19°00'N, 82°00'E. This work revealed that "the short instrumental record of ISM underestimates the magnitude of monsoon rainfall variability," and they state that "nearly every major famine in India [over the period of their study] coincided with a period of reduced monsoon rainfall as reflected in the Dandak $\delta^{18}O$ record," noting two particularly devastating famines that "occurred at the beginning of the Little Ice Age during the longest duration and most severe ISM weakening of [their] reconstruction."

Sinha *et al.* state that "ISM reconstructions from Arabian Sea marine sediments (Agnihotri *et al*., 2002; Gupta *et al*., 2003; von Rad *et al*., 1999), stalagmite $\delta^{18}O$ records from Oman and Yemen (Burns *et al*., 2002; Fleitmann *et al*., 2007), and a pollen record from the western Himalaya (Phadtare and Pant, 2006) also indicate a weaker monsoon during the Little Ice Age and a relatively stronger monsoon during the Medieval Warm Period." As a result, the eight researchers note that "since the end of the Little Ice Age, ca 1850 AD, the human population in the Indian monsoon region has increased from about 200 million to over 1 billion," and that "a recurrence of weaker intervals of ISM comparable to those inferred in our record would have serious implications to human health and economic sustainability in the region." Thus the Current Warm Period is beneficial to the population of India.

Zhang *et al*. (2007) developed flood and drought histories of the past thousand years in China's Yangtze Delta, based on "local chronicles, old and very comprehensive encyclopaedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series"—which they describe as "a powerful way to characterize the frequency, the intensity, the time position, and the duration of variations in a climate data series"—and, finally, the results of the entire set of operations were compared with two one-thousand-year temperature histories of the Tibetan Plateau: northeastern Tibet and southern Tibet.

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

The research summarized in this section shows the frequency of drought in Asia varies according to millennial, centennial, and decadal cycles. Since those cycles predate any possible human influence on climate, they serve to refute the claim that today's relatively dry climate is the result of human activity.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtasia.php.

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6.1.3. Europe

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

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

A third study of interest concerns the Danube River in western Europe, where some researchers had previously suggested that an anthropogenic signal was present in the latter decades of the twentieth century, and that it was responsible for that period's supposedly drier conditions. Ducic (2005) tested these claims by analyzing observed and reconstructed discharge rates of the river near Orsova, Serbia over the period 1731-1990. This work revealed that the lowest five-year discharge value in the pre-instrumental era (1831-1835) was practically equal to the lowest five-year discharge value in the instrumental era (1946-1950), and that the driest decade of the entire 260-year period was 1831-1840. What is more, 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," in Ducic's words, and only 0.7 percent less than the 260-year mean, leading to the conclusion that "modern discharge fluctuations do not point to dominant anthropogenic influence." In fact, Ducic's correlative analysis suggests that the detected cyclicity in the record could "point to the domination of the influence of solar activity."

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

In conclusion, there is no evidence that droughts in Europe became more frequent or more severe due to global warming in the twentieth century. Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughteurope.php.

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6.1.4. North America

6.1.4.1. Canada

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

Working in the same general area, Quiring and Papakyriakou (2005) used an agricultural drought index (Palmer's Z-index) to characterize the frequency, severity, and spatial extent of June-July moisture anomalies for 43 crop districts from the agricultural region of the Canadian prairies over the period 1920-99. This work revealed that for the 80-year period of their study, the single most severe June-July drought on the Canadian prairies occurred in 1961, and that the next most severe droughts, in descending order of severity, occurred in 1988, 1936, 1929, and 1937, for little net overall trend. Simultaneously, however, they say there was an upward trend in mean June-July moisture conditions. In addition, they note that "reconstructed July moisture conditions for the Canadian prairies demonstrate that droughts during the 18th and 19th centuries were more persistent than those of the 20th century (Sauchyn and Skinner, 2001)."

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

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

Also working in eastern Canada, Girardin *et al*. (2004) developed a 380-year reconstruction of the Canadian Drought Code (CDC, a daily numerical rating of the average moisture content of deep soil organic layers in boreal conifer stands that is used to monitor forest fire danger) for the month of July, based on 16 well-replicated tree-ring chronologies from the Abitibi Plains of eastern Canada just below James Bay. Cross-continuous wavelet transformation analyses of these data, in their words, "indicated coherency in the 8-16 and 17-32-year per cycle oscillation bands between the CDC reconstruction and the Pacific Decadal Oscillation prior to 1850," while "following 1850, the coherency shifted toward the North Atlantic Oscillation." These results led them to suggest that "the end of [the] 'Little Ice Age' over the Abitibi Plains sector corresponded to a decrease in the North Pacific decadal forcing around the 1850s," and that "this event could have been followed by an inhibition of the Arctic air outflow and an incursion of more humid air masses from the subtropical Atlantic climate sector," which may have helped reduce fire frequency and drought severity. In this regard, they note that several other paleo-climate and ecological studies have suggested that "climate in eastern Canada started to change with the end of the 'Little Ice Age' (~1850)," citing the works of Tardif and Bergeron (1997, 1999), Bergeron (1998, 2000) and Bergeron *et al*. (2001), while further noting that Bergeron and Archambault (1993) and Hofgaard *et al*. (1999) have "speculated that the poleward retreat of the Arctic air mass starting at the end of the 'Little Ice Age' contributed to the incursion of moister air masses in eastern Canada."

Moving back towards the west, Wolfe *et al*. (2005) conducted a multi-proxy hydro-ecological analysis of Spruce Island Lake in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta. Their research revealed that hydro-ecological conditions in that region varied substantially over the past 300 years, especially in terms of multi-decadal dry and wet periods. More specifically, they found that (1) recent drying in the region was not the product of Peace River flow regulation that began in 1968, but rather the product of an extended drying period that was initiated in the early to mid-1900s, (2) the multi-proxy hydro-ecological variables they analyzed were well correlated with other reconstructed records of natural climate variability, and (3) hydro-ecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with the earlier portion of the record actually depicting "markedly wetter and drier conditions compared to recent decades."

Moving to the Pacific coast of North America (Heal Lake near the city of Victoria on Canada's Vancouver Island), Zhang and Hebda (2005) conducted dendroclimatological analyses of 121 well-preserved subfossil logs discovered at the bottom of the lake plus 29 Douglas-fir trees growing nearby that led to the development of an ~ 4,000-year chronology exhibiting sensitivity to spring precipitation. In doing so, they found that "the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period." As an example of this fact, they note that spring droughts represented by ring-width departures exceeding two standard deviations below the mean in at least five consecutive years occurred in the late AD 1840s and mid 1460s, as well as the mid 1860s BC, and were more severe than any drought of the twentieth century. In addition, the most persistent drought occurred during the 120-year period between about AD 1440 and 1560. Other severe droughts of multi-decadal duration occurred in the mid AD 760s-800s, the 540s-560s, the 150s-late 190s, and around 800 BC. Wavelet analyses of the tree-ring chronology also revealed a host of natural oscillations on timescales of years to centuries, demonstrating that the twentieth century was in no way unusual in this regard, as there were many times throughout the prior 4,000 years when it was both wetter and drier than it was during the last century of the past millennium.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtcanada.php.

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6.1.4.2. Mexico

Stahle *et al*. (2000) developed a long-term history of drought over much of North America from reconstructions of the Palmer Drought Severity Index, based on analyses of many lengthy tree-ring records. This history reveals the occurrence of a sixteenth century drought in Mexico that persisted from the 1540s to the 1580s. Writing of this anomalous period of much reduced precipitation, they say that "the 'megadrought' of the sixteenth century far exceeded any drought of the 20th century."

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

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

With respect to the twentieth century alone, there was also a long period of high winter-spring precipitation that stretched from 1905 to 1932; following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record. Finally, with respect to the entire 346 years, there is no long-term trend in the data, nor is there any evidence of any sustained departure from that trend over the course of the twentieth century.

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

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

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

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

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

Based on the many results described above, it is evident that throughout much of Mexico some of the driest conditions and worst droughts of the Late Holocene occurred during the Little Ice Age and the latter part of the Dark Ages Cold Period. These observations do much to discredit the model-based claim that droughts will get worse as air temperatures rise. All of the Mexican droughts of the twentieth century (when the IPCC claims the planet warmed at a rate and to a level that were unprecedented over the past two millennia) were much milder than many of the droughts that occurred during much colder centuries.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtmexico.php.

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6.1.4.3. United States

6.1.4.3.1. Central United States

Starting at the U.S.-Canadian border and working our way south, we begin with the study of Fritz *et al*. (2000), who utilized data derived from sediment cores retrieved from three North Dakota lakes to reconstruct a 2,000-year history of drought in this portion of the Northern Great Plains. This work suggested, in their words, "that droughts equal or greater in magnitude to those of the Dust Bowl period were a common occurrence during the last 2000 years."

Also working in the Northern Great Plains, but extending down into South Dakota, Shapley *et al*. (2005) developed a 1,000-year hydroclimate reconstruction from local bur oak tree-ring records and various lake sediment cores. Based on this record, they determined that prior to 1800, "droughts tended towards greater persistence than during the past two centuries," suggesting that droughts of the region became shorter-lived as opposed to longer-lasting as the earth gradually recovered from the cold temperatures of the Little Ice Age.

The above observations are significant because the United States' Northern Great Plains is an important agricultural region, providing a significant source of grain for both local and international consumption. However, the region is susceptible to periodic extreme droughts that tend to persist longer than those in any other part of the country (Karl *et al*., 1987; Soule, 1992). Because of this fact, Laird *et al*. (1998) examined the region's historical record of drought in an attempt to establish a baseline of natural drought variability that could help in attempts to determine if current and future droughts might be anthropogenically influenced.

Working with a high-resolution sediment core obtained from Moon Lake, North Dakota, which provided a sub-decadal record of salinity (drought) over the past 2,300 years, Laird *et al*. discovered that the U.S. Northern Great Plains were relatively wet during the final 750 years of this period. Throughout the 1,550 prior years, they determined that "recurring severe droughts were more the norm," and that they were "of much greater intensity and duration than any in the 20th century," including the great Dust Bowl event of the 1930s. There were, as they put it, "no modern equivalents" to Northern Great Plains droughts experienced prior to AD 1200, which means the human presence has not led to unusual drought conditions in this part of the world.

Continuing our southward trek, we encounter the work of Forman *et al*. (2005), who note that "periods of dune reactivation reflect sustained moisture deficits for years to decades and reflect broader environmental change with diminished surface- and ground-water resources." This observation prompted them to focus on "the largest dune system in North America, the Nebraska Sand Hills," where they utilized "recent advances in optically stimulated luminescence dating (Murray and Wintle, 2000) to improve chronologic control on the timing of dune reactivation." They also linked landscape response to drought over the past 1,500 years to tree-ring records of aridity.

Forman *et al*. identified six major aeolian depositional events in the past 1,500 years, all but one of which (the 1930s "Dust Bowl" drought) occurred prior to the twentieth century. Moving backwards in time from the Dust Bowl, the next three major events occurred during the depths of the Little Ice Age, the next one near the Little Ice Age's inception, and the earliest one near the end of the Dark Ages Cold Period. As for how the earlier droughts compare with those of the past century, the researchers say the

1930s drought (the twentieth century's worst depositional event) was less severe than the others, especially the one that has come to be known as the sixteenth century megadrought. Forman *et al*. thus conclude that the aeolian landforms they studied "are clear indicators of climate variability beyond twentieth century norms, and signify droughts of greater severity and persistence than thus far instrumentally recorded."

In a study that covered the entirety of the U.S. Great Plains, Daniels and Knox (2005) analyzed the alluvial stratigraphic evidence for an episode of major channel incision in tributaries of the upper Republican River that occurred between 1,100 and 800 years ago, after which they compared their findings with proxy drought records from 28 other locations throughout the Great Plains and surrounding regions. This work revealed that channel incision in the Republican River between about AD 900 and 1200 was well correlated with a multi-centennial episode of widespread drought, which in the words of Daniels and Knox, "coincides with the globally recognized Medieval Warm Period." Of great interest, however, is the fact that modern twentieth century warming has *not* led to a repeat of those widespread drought conditions.

Working in pretty much the same area some seven years earlier, Woodhouse and Overpeck (1998) reviewed what we know about the frequency and severity of drought in the central United States over the past two thousand years based upon empirical evidence of drought from various proxy indicators. Their study indicated the presence of numerous "multidecadal- to century-scale droughts," leading them to conclude that "twentieth-century droughts are not representative of the full range of drought variability that has occurred over the last 2000 years." In addition, they noted that the twentieth century was characterized by droughts of "moderate severity and comparatively short duration, relative to the full range of past drought variability."

With respect to the causes of drought, Woodhouse and Overpeck suggest a number of different possibilities that either directly or indirectly induce changes in atmospheric circulation and moisture transport. However, they caution that "the causes of droughts with durations of years (i.e., the 1930s) to decades or centuries (i.e., paleodroughts) are not well understood." They conclude that "the full range of past natural drought variability, deduced from a comprehensive review of the paleoclimatic literature, suggests that droughts more severe than those of the 1930s and 1950s are likely to occur in the future," whatever the air's CO_2 concentration or temperature might.

Mauget (2004) looked for what he called "initial clues" to the commencement of the great drying of the U.S. Heartland that had been predicted to occur in response to CO_2-induced global warming by Manabe and Wetherald (1987), Rind *et al*. (1990), Rosenzweig and Hillel (1993), and Manabe *et al*. (2004), which Mauget reasoned would be apparent in the observational streamflow record of the region. In this endeavor, he employed data obtained from the archives of the U.S. Geological Survey's Hydro-Climatic Data Network, which come from 42 stations covering the central third of the United States that stretch from the Canadian border on the north to the Gulf of Mexico on the south, with the most dense coverage being found within the U.S. Corn Belt.

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

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

Mauget states that the streamflow data "suggest a fundamental climate shift, as the most significant incidence of high ranked annual flow was found over relatively long time scales at the end of the data record." In other words, the shift is *away from* the droughty conditions predicted by the IPCC to result from CO_2-induced global warming in this important agricultural region of the United States.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtusacentral.php.

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6.1.4.3.2. Eastern United States

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

Building upon the work of Cronin *et al*. were Willard *et al*. (2003), who examined the last 2,300 years of the Holocene record of Chesapeake Bay and the adjacent terrestrial ecosystem "through the study of fossil dinoflagellate cysts and pollen from sediment cores." In doing so, they found that "several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records." The first of these periods of lower-than-average precipitation (200 BC-AD 300) occurred during the latter part of the Roman Warm Period, while the next such period (~AD 800-1200), according to Willard *et al*., "corresponds to the 'Medieval Warm Period'." In addition, they identified several decadal-scale dry intervals that spanned the years AD 1320-1400 and 1525-1650.

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

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

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

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtusaeast.php.

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6.1.4.3.3. Western United States

Is there evidence of more severe and longer-lasting droughts in the western United States? We begin our journey of inquiry just below Canada, in the U.S. Pacific Northwest, from whence we gradually wend our way to the U.S./Mexico border.

Knapp *et al*. (2002) created a 500-year history of severe single-year Pacific Northwest droughts from a study of 18 western juniper tree-ring chronologies that they used to identify what they call extreme Climatic Pointer Years or CPYs, which are indicative of severe single-year droughts. As they describe it, this procedure revealed that "widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries," while "both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread." Thereafter, however, they say that "CPYs became more numerous during the 20th century," although the number of twentieth century extreme CPYs (26) was still substantially less than the mean of the number of sixteenth and seventeenth century extreme CPYs (38), when the planet was colder. The data of this study fail to support the IPCC's claim that global warming increases the frequency of severe droughts.

Gedalof *et al*. (2004) used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water-year flow on the Columbia River at The Dales in Oregon since 1750. This study of the second-largest drainage basin in the United States is stated by them to have been done "for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events." When finished, it revealed, in their words, that "persistent low flows during the 1840s were probably the most severe of the past 250 years," and that "the drought of the 1930s is probably the second most severe."

More recent droughts, in the words of the researchers, "have led to conflicts among uses (e.g., hydroelectric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of access to water (in particular junior water rights holders in the agricultural sector)." Nevertheless, they say that "these recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events." In fact, they say, "the period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events."

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

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

In another study based on sediment cores extracted from Pyramid Lake, Nevada, Mensing *et al*. (2004) analyzed pollen and algal microfossils deposited there over the prior 7,630 years that allowed them to infer the hydrologic history of the area over that time period. Their results indicated that "sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet," but, paradoxically, that "the past 2500 yr have been marked by recurring persistent droughts." The longest of these droughts, according to them, "occurred between 2500 and 2000 cal yr B.P.," while others occurred "between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P," with none recorded in more recent warmer times.

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

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

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

Working in the central and southern Rocky Mountains, Gray *et al*. (2003) examined 15 tree ring-width chronologies that had been used in previous reconstructions of drought for evidence of low-frequency variations in five regional composite precipitation histories. In doing so, they found that "strong multidecadal phasing of moisture variation was present in all regions during the late 16th-century megadrought," and that "oscillatory modes in the 30-70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." They thus speculate that "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase Pacific Decadal Oscillation with the warm phase Atlantic Multidecadal Oscillation," which is something they envision as having happened in both the severe 1950s drought and the late sixteenth century megadrought. Hence, there is reason to believe that episodes of extreme dryness in this part of the country may be driven in part by naturally recurring climate "regime shifts" in the Pacific and Atlantic Oceans.

Hidalgo *et al*. (2000) used a new form of principal components analysis to reconstruct a history of streamflow in the Upper Colorado River Basin based on information obtained from tree-ring data, after which they compared their results to those of Stockton and Jacoby (1976). In doing so, they found the two approaches to yield similar results, except that Hidalgo *et al*.'s approach responded with more intensity to periods of below-average streamflow or regional drought. Hence, it was easier for them to determine there has been "a near-centennial return period of extreme drought events in this region," going all the way back to the early 1500s. It is reasonable to assume that if such an extreme drought were to commence today, it would not be related to either the air's CO_2 content or its temperature.

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

"Overall," in the words of the three researchers, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." In fact, they conclude from their work that "droughts more severe than any 20th to 21st century event occurred in the past," meaning the preceding few centuries.

Moving closer still to the U.S. border with Mexico, Ni *et al.* (2002) developed a 1,000-year history of cool-season (November-April) precipitation for each climate division of Arizona and New Mexico from a network of 19 tree-ring chronologies. They determined that "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570-97, 1664-70, the 1740s, the 1770s, and the late 1800s." They also note that although the 1950s drought was large in both scale and severity, "it only lasted from approximately 1950 to 1956," whereas the sixteenth century mega-drought lasted more than four times longer.

With respect to the opposite of drought, Ni *et al.* report that "several wet periods comparable to the wet conditions seen in the early 1900s and after 1976" occurred in "1108-20, 1195-1204, 1330-45, the 1610s, and the early 1800s," and they add that "the most persistent and extreme wet interval occurred in the 1330s." Consequently, for the particular part of the world covered by Ni *et al.*'s study, there appears to be nothing unusual about the extremes of both wetness and dryness experienced during the twentieth century.

Also working in New Mexico, Rasmussen *et al.* (2006) derived a record of regional relative moisture from variations in the annual band thickness and mineralogy of two columnar stalagmites collected from Carlsbad Cavern and Hidden Cave in the Guadalupe Mountains near the New Mexico/Texas border. From this work they discovered that both records "suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record."

We come now to two papers that deal with the western United States as a whole. In the first, Cook *et al.* (2004) developed a 1,200-year history of drought for the western half of the country and adjacent parts of Canada and Mexico (hereafter the "West"), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index that were derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66 percent of them) possessed data that extended back to AD 800. This reconstruction, in the words of Cook *et al.*, revealed "some remarkable earlier increases in aridity that *dwarf* [our italics] the comparatively short-duration current drought in the 'West'." Interestingly, they report that "the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occur during a ~400 year interval of overall elevated aridity from AD 900 to 1300," which they say is "broadly consistent with the Medieval Warm Period."

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

While we agree with Cook *et al.*'s conclusion, we cannot help but note that the droughts that occurred during the Medieval Warm Period were obviously not CO_2-induced. If the association between global warmth and drought in the western United States is robust, it suggests that current world temperatures are still well below those experienced during large segments of the Medieval Warm Period.

The last of the two papers to cover the western United States as a whole is that of Woodhouse

(2004), who reports what is known about natural hydroclimatic variability throughout the region via descriptions of several major droughts that occurred there over the past three millennia, all but the last century of which had atmospheric CO_2 concentrations that never varied by more than about 10 ppm from a mean value of 280 ppm.

For comparative purposes, Woodhouse begins by noting that "the most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts." The first of these lasted "most of the decade of the 1930s" and "occurred in several waves," while the latter "also occurred in several waves over the years 1951-1956." More severe than either of these two droughts was what has come to be known as the Sixteenth Century Megadrought, which lasted from 1580 to 1600 and included northwestern Mexico in addition to the southwestern United States and the western Great Plains. Then there was what is simply called The Great Drought, which spanned the last quarter of the thirteenth century and was actually the last in a series of three thirteenth century droughts, the first of which may have been even more severe than the last. In addition, Woodhouse notes there was a period of remarkably sustained drought in the second half of the twelfth century.

It is evident from these observations, according to Woodhouse, that "the 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records." This subset, as it pertains to water shortage, does not approach the level of drought severity and duration experienced in prior centuries and millennia. A drought much more extreme than the most extreme droughts of the twentieth century would be required to propel the western United States and adjacent portions of Canada and Mexico into a truly unprecedented state of dryness.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtusawest.php.

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6.1.4.3.4. Entire United States

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

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

Going back considerably further in time, Fye *et al*. (2003) developed gridded reconstructions of the summer (June-August) basic Palmer Drought Severity Index over the continental United States, based on "annual proxies of drought and wetness provided by 426 climatically sensitive tree-ring chronologies." This work revealed that the greatest twentieth century moisture anomalies across the United States were the 13-year pluvial over the West in the early part of the century, and the epic droughts of the 1930s (the Dust Bowl years) and 1950s, which lasted 12 and 11 years, respectively.

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

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

Last, we come to the intriguing study of Herweijer *et al*. (2006), who begin the report of their work by noting that "drought is a recurring major natural hazard that has dogged civilizations through time and remains the 'world's costliest natural disaster'." With respect to the twentieth century, they report that the "major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA." However, they add that "these events are not unique to the twentieth century," and they go on to describe three periods of widespread and persistent drought in the latter half of the nineteenth century—1856-1865 (the "Civil War" drought), 1870-1877 and 1890-1896—based on evidence obtained from proxy, historical, and instrumental data.

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

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

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

But how is it that simultaneous global-scale warmth and regional-scale cold combine to produce the most severe North American droughts? One possible answer is variable solar activity. When solar activity is in an ascending mode, the globe as a whole warms; but at the same time, to quote from Herweijer *et al*.'s concluding sentence, increased irradiance typically "corresponds to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions."

An important implication of these observations is that the most severe North American droughts should occur during major multi-centennial global warm periods, as has in fact been observed to be the case. Since the greatest such droughts of the Current Warm Period have not yet approached the severity of those that occurred during the Medieval Warm Period, it seems a good bet that the global temperature of the Current Warm Period is not yet as high as the global temperature that prevailed throughout the Medieval Warm Period.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/d/droughtusa.php.

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6.2. Floods

In the midst of 2002's massive flooding in Europe, Gallus Cadonau, the managing director of the Swiss Greina Foundation, called for a punitive tariff on U.S. imports to force cooperation on reducing greenhouse gas emissions, claiming that the flooding "definitely has to do with global warming" and stating that "we must change something now" (Hooper, 2002). Cadonau was joined in this sentiment by Germany's environment minister, Jurgen Trittin, who implied much the same thing when he said "if we don't want this development to get worse, then we must continue with the consistent reduction of environmentally harmful greenhouse gasses" (Ibid.).

The IPCC seems to agree with Cadonau and Trittin. Its authors report "a catastrophic flood occurred along several central European rivers in August 2002. The floods resulting from extraordinarily high precipitation were enhanced by the fact that the soils were completely saturated and the river water levels were already high because of previous rain. Hence, it was part of a pattern of weather over an extended period" (IPCC, 2007-I, p. 311). While admitting "there is no significant trend in flood occurrences of the Elbe within the last 500 years," the IPCC nevertheless says the "observed increase in precipitation variability at a majority of German precipitation stations during the last century is indicative of an enhancement of the probability of both floods and droughts" (Ibid.)

In evaluating these claims it is instructive to see how flood activity has responded to the global warming of the past century. In the sections below we review studies of the subject that have been conducted in Asia, Europe, and North America.

Additional information on this topic, including reviews on floods not discussed here, can be found at http://www.co2science.org/subject/f/subject_f.php under the heading Floods.

6.2.1. Asia

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

Two years later, Kale *et al*. (2003) conducted geomorphic studies of slackwater deposits in the bedrock gorges of the Tapi and Narmada Rivers of central India, which allowed them to assemble long chronologies of large floods of these rivers. In doing so, they found that "since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837." With respect to large floods on the Narmada River, they reported at least nine or 10 floods between the beginning of the Christian era and AD 400; between AD 400 and 1000 they documented six to seven floods; between AD 1000 and 1400 eight or nine floods; and after 1950 three more such floods. In addition, on the basis of texture, elevation, and thickness of the flood units, they concluded that "the periods AD 400-1000 and post-1950 represent periods of extreme floods."

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

Little Ice Age. There appears to be little correlation between the flood characteristics of the Tapi and Narmada Rivers of central India and the thermal state of the global climate.

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

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

The following year, Davi *et al*. (2006) developed a reconstruction of streamflow that extended from 1637 to 1997, based on absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia, all of which sites were in or near the Selenge River basin, the largest river in Mongolia. Of the 10 wettest five-year periods, only two occurred during the twentieth century (1990-1994 and 1917-1921, the second and eighth wettest of the 10 extreme periods, respectively), once again indicative of a propensity for less flooding during the warmest portion of the 360-year period.

The year 2007 produced a second study of the Yangtze Delta of Eastern China, when Zhang *et al*. (2007) developed flood and drought histories of the past thousand years "from local chronicles, old and very comprehensive encyclopaedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series" and, finally, the results of the entire set of operations were compared with 1,000-year temperature histories of northeastern Tibet and southern Tibet. This work revealed, in the words of the researchers, that "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region."

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

The history of floods in Asia provides no evidence of increased frequency or severity during the Current Warm Period. Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/ subject/f/floodsasia.php.

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6.2.2. Europe

Nesje *et al*. (2001) analyzed a sediment core from a lake in southern Norway in an attempt to determine the frequency and magnitude of floods in that region. The last thousand years of the record revealed “a period of little flood activity around the Medieval period (AD 1000-1400),” which was followed by a period of extensive flood activity that was associated with the “post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the ‘Little Ice Age’.” This particular study suggests that the post-Little Ice Age warming the earth has experienced for the past century or two—and which could well continue for some time to come—should be leading this portion of the planet into a period of less-extensive floods.

Pirazzoli (2000) analyzed tide-gauge and meteorological data over the period 1951-1997 for the northern portion of the Atlantic coast of France, discovering that the number of atmospheric depressions and strong surge winds in this region “are becoming less frequent.” The data also revealed that “ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding,” which is what would be expected in view of the findings of Nesje *et al*.

Reynard *et al*. (2001) used a continuous flow simulation model to assess the impacts of potential climate and land use changes on flood regimes of the UK’s Thames and Severn Rivers; and, as might have been expected of a model study, it predicted modest increases in the magnitudes of 50-year floods on these rivers when the climate was forced to change as predicted for various global warming scenarios. However, when the modelers allowed forest cover to rise concomitantly, they found that this land use change “acts in the opposite direction to the climate changes and under some scenarios is large enough to fully compensate for the shifts due to climate.” As the air’s CO_2 content continues to rise, there will be a natural impetus for forests to expand their ranges and grow in areas where grasses now dominate the landscape. If public policies cooperate, forests will indeed expand their presence on the river catchments in question and neutralize any predicted increases in flood activity in a future high-CO_2 world.

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

Mudelsee *et al*. (2003) analyzed historical documents from the eleventh century to 1850, plus subsequent water stage and daily runoff records from then until 2002, for two of the largest rivers in central Europe: the Elbe and Oder Rivers. The team of German scientists reported that “for the past 80 to 150 years”—which the IPCC claims was a period of unprecedented global warming—“we find a decrease in winter flood occurrence in both rivers, while summer floods show no trend, consistent with trends in extreme precipitation occurrence.” As the world has recovered from the global chill of the Little Ice Age, flooding of the Elbe and Oder rivers has not materially changed in summer and has actually decreased in winter. Blaming anthropogenic CO_2 emissions for the European flooding of 2002, then, is not a reasoned deduction based on scientific evidence.

On September 8 and 9, 2002, extreme flooding of the Gardon River in southern France occurred as a result of half-a-year’s rainfall being received in approximately 20 hours. Floods claimed the lives of a number of people and caused much damage to towns and villages situated adjacent to its channel. The event elicited much coverage in the press; in the words of Sheffer *et al*. (2003), “this flood is now considered by the media and professionals to be ‘the largest flood on record’,” which record extends all the way back to 1890. Coincidently, Sheffer *et al*. were in the midst of a study of prior floods of the Gardon River, so they had data spanning a much longer time period. They report that “the extraordinary flood of September 2002 was not the largest by any means,” noting that “similar, and even larger floods have occurred several times in the recent past,” with three of the five greatest floods they had identified to that point in time occurring over the period AD 1400-1800 during the Little Ice Age. Commenting on these facts, Sheffer *et al*. stated that “using a longer time scale than human collective memory, paleoflood studies can put in perspective the occurrences of the extreme floods that hit Europe and other parts of the world during the summer of 2002.”

Lindstrom and Bergstrom (2004) analyzed runoff and flood data from more than 60 discharge stations scattered throughout Sweden, some of which provide information stretching to the early- to mid-1800s, when Sweden and the world were still experiencing the cold of the Little Ice Age. This analysis led them to discover that the last 20 years of the past century were indeed unusually wet, with a runoff anomaly of +8 percent compared with the century average. But they also found that “the runoff in the 1920s was comparable to that of the two latest decades,” and that “the few observation series available from the 1800s show that the runoff was even higher than recently.” What is more, they note that “flood peaks in old data are probably underestimated,” which “makes it difficult to conclude that there has really been a significant increase in average flood levels.” In addition, they say “no increased frequency of floods with a return period of 10 years or more, could be determined.”

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

It is clear that for most of Europe, there are no compelling real-world data to support the claim that the global warming of the past two centuries led to more frequent or severe flooding. Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/f/floodseuro.php.

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6.2.3. North America

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

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

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

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

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

In spite of the general tendencies described in these several papers, there still were some significant floods during the last decade of the past century, such as the 1997 flooding of the Red River of the North, which devastated Grand Forks, North Dakota, as well as parts of Canada. However, as Haque (2000) reports, although this particular flood was indeed the largest experienced by the Red River over the past century, it was not the largest to occur in historic times. In 1852 there was a slightly larger Red River flood, and in 1826 there was a flood that was nearly 40 percent greater than the flood of 1997. The temperature of the globe was colder at the times of these earlier catastrophic floods than it was in 1997, indicating that one cannot attribute the strength of the 1997 flood to higher temperatures that year or the warming of the preceding decades. We also note that Red River flooding is also linked to snow melt and ice jams because itflows northward into frozen areas.

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

Expanding the scope of our survey to much longer intervals of time is Fye *et al*. (2003), who developed multi-century reconstructions of summer (June-August) Palmer Drought Severity Index over the continental United States from annual proxies of moisture status provided by 426 climatically sensitive tree-ring chronologies. This exercise indicated that the greatest twentieth century wetness anomaly across the United States was a 13-year period in the early part of the century when it was colder than it is now. Fye *et al*.'s analysis also revealed the existence of a 16-year pluvial from 1825 to 1840 and a prolonged 21-year wet period from 1602 to 1622, both of which anomalies occurred during the Little Ice Age, when, of course, it was colder still.

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

Also working with tree-ring chronologies, Ni *et al*. (2002) developed a 1,000-year history of cool-season (November-April) precipitation for each climate division in Arizona and New Mexico, USA. In doing so, they found that several wet periods comparable to the wet conditions seen in the early 1900s and post-1976 occurred in 1108-20, 1195-1204, 1330-45 (which they denominate "the most persistent and extreme wet interval"), the 1610s, and the early 1800s, all of which wet periods are embedded in the long cold expanse of the Little Ice Age, which is clearly revealed in the work of Esper *et al*. (2002).

Doubling the temporal extent of Ni *et al*.'s investigation, Schimmelmann *et al*. (2003) analyzed gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, USA, which they accurately dated by varve-counting. Their analysis indicated that six prominent flood events occurred 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 that "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells," that "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)," and that "the flood of ~AD 1418 occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al*., 1997; Meeker and Mayewski, 2002)." As a result, they hypothesize that "solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years," and that "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note that "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." Consequently, if such flooding does occur in the near future, there will be no need to suppose it came as a consequence of what the IPCC calls the unprecedented warming of the past century.

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

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

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

Taken together, the research described in this section suggests that North American flooding tends to become both less frequent and less severe when the planet warms, although there have been some exceptions to this general rule. We would expect that any further warming of the globe would tend to further reduce both the frequency and severity of flooding in North America.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/f/floodsnortham.php.

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6.3. Tropical Cyclones

The IPCC contends that global warming is likely to increase the frequency and intensity of hurricanes. For example, it states "it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures [italics in the original]" (IPCC, 2007-I, p. 15). However, numerous peer-reviewed studies suggest otherwise. In the following sections we examine such claims as they pertain to hurricane activity in the Atlantic, Pacific, and Indian Ocean basins, and the globe as a whole.

Reference

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.

6.3.1. Atlantic Ocean

6.3.1.1. Intensity

Free *et al*. (2004) write that "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998)," but that "because the predicted increase in intensity for doubled CO_2 is only 5%-20%, changes over the past 50 years would likely be less than 2%—too small to be detected easily." They report that "studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al*., 1996; Henderson-Sellers *et al*., 1998; Solow and Moore, 2002)," and set out to find increases in what they call "potential" hurricane intensity, because, as they describe it, "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity." Using radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans, they compare their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They report that their results "show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

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

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

By 2050, Pielke *et al*. report that "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between $22 and $60 of increase in damage due to population growth and wealth," citing the findings of Pielke *et al*. (2000) in this regard. Based on this evidence, they state without equivocation that "the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms."

In concluding their review, Pielke *et al*. note that massive reductions of anthropogenic CO_2 emissions "simply will not be effective with respect to addressing future hurricane impacts," and that "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

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

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

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

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

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

In a closely related paper, Vecchi and Soden (2007b) used both climate models and observational reconstructions "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They found "changes in local sea surface temperature are inadequate for characterizing *even the sign* [our italics] of changes in potential intensity." Instead, they report that "long-term changes in potential intensity are closely related to the regional structure of warming," such that "regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa." Using this relationship to reconstruct changes in potential intensity over the twentieth century, based on observational reconstructions of sea surface temperature, they further found that "even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably peaked in the 1930s and 1950s," noting that "recent values are near the historical average." The two scientists' conclusion was that the response of tropical cyclone activity to natural climate variations "may be larger than the response to the more uniform patterns of greenhouse-gas-induced warming."

Also in the year 2007, and at the same time Vecchi and Soden were conducting their studies of the subject, Latif *et al*. (2007) were analyzing the 1851-2005 history of Accumulated Cyclone Energy

(ACE) Index for the Atlantic basin, which parameter, in their words, "takes into account the number, strength and duration of all tropical storms in a season," after which they "analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870-2003."

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

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

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

Latif *et al*. say "the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region," and "changes in the meridianal overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered," and that "changes in ENSO statistics in the tropical Pacific may become important." Consequently, it is anyone's guess as to what would actually occur in the real world if the earth were to experience additional substantial warming. However, since the global temperature rise of the twentieth century—which the IPCC contends was unprecedented over the past two millennia—did not lead to a sustained long-term increase in hurricane intensity, there is little reason to believe any further warming would do so.

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

As a result of these efforts, the two researchers determined that "alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales." Of special interest in this regard, as they describe it, is the fact that "several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550-1850 AD) when sea surface temperatures were generally colder than present," but that "no major hurricanes have impacted this area since 1893," when the earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

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

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

In light of the many real-world observations (as well as certain modeling work) discussed above, it would appear that even the supposedly unprecedented global warming of the past century or more has not led to an increase in the intensity of Atlantic hurricanes.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanintensity.php.

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6.3.1.2. Frequency

6.3.1.2.1. The Past Few Millennia

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? We offer a brief review of some studies that have explored this question via thousand-year reconstructions of the region's intense hurricane activity.

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

Seven years later, Liu and Fearn (2000) conducted a similar study based on 16 sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico that covered the past 7,000 years. In this study, 12 major hurricanes of category 4 or 5 intensity were found to have struck the Western Lake region. Nearly all of these events were centered on a 2,400-year period between 1,000 and 3,400 years ago, when 11 of the 12 events were recorded. In contrast, between 0 to 1,000 and 3,400 to 7,000 years ago, only one and zero major hurricane strikes were recorded, respectively. According to the two researchers, a probable explanation for the "remarkable increase in hurricane frequency and intensity" that affected the Florida Panhandle and the Gulf Coast after 1400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift south and the Bermuda High southwest of their earlier Holocene positions, such as would be expected with global cooling, giving strength to their contention that "paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime."

Last, we have the study of Donnelly and Woodruff (2007), who state that "it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones," citing the studies of Emanuel (2005) and Webster *et al*. (2005). Donnelly and Woodruff developed "a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls."

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

In light of these findings, Donnelly and Woodruff concluded that "the information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia." Indeed, there is no compelling reason to believe that the current level of intense hurricane activity is in any way unprecedented or that it has been caused by global warming. Quite to the contrary, the two researchers write that "studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al*., 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development."

In summary, millennial-scale reconstructions of intense hurricane activity within the Atlantic Basin provide no support for the claim that global warming will lead to the creation of more intense Atlantic hurricanes that will batter the east, southeast, and southern coasts of the United States. In fact, they suggest just the opposite.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanmill.php.

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6.3.1.2.2. The Past Few Centuries

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

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

Boose *et al*. (2001) used historical records to reconstruct hurricane damage regimes for an area composed of the six New England states plus adjoining New York City and Long Island for the period 1620-1997. In describing their findings, they wrote that "there was no clear century-scale trend in the number of major hurricanes." At lower damage levels, however, fewer hurricanes were recorded in the seventeenth and eighteenth centuries than in the nineteenth and twentieth centuries; but the three researchers concluded that "this difference is probably the result of improvements in meteorological observations and records since the early 19th century." Confining ourselves to the better records of the past 200 years, we note that the cooler nineteenth century had five of the highest-damage storms, while the warmer twentieth century had only one such storm.

Nyberg *et al*. (2007) developed a history of major (category 3-5) Atlantic hurricanes over the past 270 years based on proxy records of vertical wind shear and sea surface temperature that they derived from corals and a marine sediment core. These parameters are the primary controlling forces that set the stage for the formation of major hurricanes in the main development region westward of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10 and 20°N, where 85 percent of all major hurricanes and 60 percent of all non-major hurricanes and tropical storms of the Atlantic are formed. This effort resulted in their discovering that the average frequency of major Atlantic hurricanes "decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s." More specifically, they note that "a gradual downward trend is evident from an average of ~4.1 (1775-1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s," and that "the current active phase (1995-2005) is unexceptional compared to the other high-activity periods of ~1756-1774, 1780-1785, 1801-1812, 1840-1850, 1873-1890 and 1928-1933." They conclude that the recent ratcheting up of Atlantic major hurricane activity appears to be simply "a recovery to normal hurricane activity." In a commentary on Nyberg *et al*.'s paper, Elsner (2007) states that "the assumption that hurricanes are simply passive responders to climate change should be challenged."

Also noting that "global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean," with the implication that "a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State," Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005, in order to assess the degree of likelihood that twentieth century global warming might be influencing these storms, particularly for hurricanes but also for tropical storms, tropical depressions and extratropical storms.

This work revealed, in Vermette's words, that "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and that of these storms, 14 were hurricanes, 27 were tropical storms, seven were tropical depressions and 28 were extratropical storms. For Long Island, he further reports that "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." Also of note is his finding that storm activity was greatest in both the late nineteenth century and the late twentieth century, and the fact that "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century." As a result, Vermette concludes that "rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century." He also concludes that "yet unanswered is whether a warmer global climate of the future will take hurricane activity beyond what has been experienced in the observed record."

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

In discussing his findings, the University of South Carolina researcher says that "the modern records which cover just a little over a hundred years is too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude." In addition, he states that "if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [they] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005." We also observe that the new record clearly indicates that the planet's current high levels of air temperature and CO_2 concentration cannot be blamed for the 2005 Katrina catastrophe, as both parameters were much lower when tropical cyclone and hurricane activity in that region were much higher in the early- to mid-1800s.

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

In light of these findings, the two researchers conclude that "the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes," and they say that to this point in time, "warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes." As for the years and decades ahead, they write that "whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans."

Vecchi and Knutson (2008) write in the introduction to their study of the subject that "there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency." In further exploring this question, they derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) that were missed by the observing system in the pre-satellite era (1878-1965), after which they analyzed trends of both reconstructed TC numbers and duration over various time periods and looked at how they may or may not have been related to trends in sea surface temperature over the main development region of North Atlantic TCs. This work revealed, in their words, that "the estimated trend for 1900-2006 is highly significant (+~4.2 storms century^{-1})," but they say that the trend "is strongly influenced by a minimum in 1910-30, perhaps artificially enhancing significance." When using their base case adjustment for missed TCs and considering the entire 1878-2006 record, they find that the trend in the number of TCs is only "weakly positive" and "not statistically significant," while they note that the trend in average TC duration over the 1878-2006 period "is negative and highly significant."

Elsner (2008), in his summary of the *International Summit on Hurricanes and Climate Change* held in May 2007 on the Greek island of Crete, said the presence of more hurricanes in the northeastern Caribbean Sea "during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today" provides evidence that "today's warmth is not needed for increased storminess."

In conclusion, the bulk of the evidence that has been accumulated to date over multi-century timescales indicates that late twentieth century yearly hurricane numbers were considerably lower than those observed in colder prior centuries. It is by no means clear that further global warming, due to any cause, would lead to an increase or decrease in U.S. landfalling hurricanes. All we can say is that up to this point in time, global warming appears to have had a weak negative impact on their numbers.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlancent.php.

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6.3.1.2.3. The Past Century

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what the IPCC describes as unprecedented global warming? This became a matter of intense speculation following a spike of storm occurrences in 2004-2005, but once again it is instructive to approach the question by starting with the findings of earlier research.

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

Noting that the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but that during the preceding four years (1991-94) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al*. (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. In doing so, they found that "perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region." They also noted that "in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea-level pressure, abnormally warm ocean waters, and very humid values of total precipitable water."

An additional factor that may have contributed to the enhanced activity of the 1995 Atlantic hurricane season was the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Possibly the most important factor of all, however, was what Landsea *et al*. called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions," which contributed to what they described as "the dramatic reversal" of weather characteristics "which dominated during the [prior] four hurricane seasons."

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

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al*. (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944-1996, decreasing trends were found for (1) the total number of hurricanes, (2) the number of intense hurricanes, (3) the annual number of hurricane days, (4) the maximum attained wind speed of all hurricane storms averaged over the course of a year, and (5) the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they reported that the total number of Atlantic hurricanes making landfall in the United States had decreased over the 1899-1996 time period, and that normalized trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of $728 million per decade.

In a similar study that included a slightly longer period of record (1935-1998), Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States, finding that "a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of -0.011 ± 0.0086 storms per year." To drive home the significance of that result, they expressly called attention to the fact that "the estimated trend slope is negative," which means, of course, that the yearly number of such storms is decreasing, which is just the opposite of what they described as the "frequent hypothesis ... that global warming is causing increased storm activity." Their statistical analysis indicates that "the trend slope is not significantly different from zero."

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

Lupo and Johnston (2000) found "there has been relatively little trend in the overall occurrence of hurricanes within the Atlantic Ocean Basin (62 year period)," reflecting an upward trend in category 1 hurricanes which is countered by downward or weak trends in the occurrence of category 2-5 hurricanes. Stratifying by hurricane genesis region indicated the tendency for more hurricanes to form in La Niña years during PDO1 (1977-1999) was strongly influenced by more storms being generated in the Caribbean and Eastern Atlantic. Only two storms formed in these regions during El Niño years. During PDO2 (1947-1976) there was a weak tendency for more (fewer) storms forming in the Gulf and Caribbean (West and East Atlantic) sub-regions during La Niña years, while the reverse occurred for El Niño years.

Three years later, Balling and Cerveny (2003) wrote that "many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones," but that empirical studies had failed to reveal any such relationships. They also noted that "some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events," and that these relationships have not been thoroughly studied with historical real-world data. They proceeded to fill this void by conducting such a study for tropical storms in the Caribbean Sea, the Gulf of Mexico, and the western North Atlantic Ocean.

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

Elsner *et al*. (2004) conducted a changepoint analysis of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the twentieth century, which technique, in their words, "quantitatively identifies temporal shifts in the mean value of the observations." This work revealed that "major North Atlantic hurricanes have become more frequent since 1995," but at "a level reminiscent of the 1940s and 1950s." In actuality, however, they had not quite reached that level, nor had they maintained it for as long a time. Their data indicate that the mean annual hurricane count for the seven-year period 1995-2001 was 3.86, while the mean count for the 14-year period 1948-1961 was 4.14. They also reported that, "in general, twentieth-century U.S. hurricane activity shows no abrupt shifts," noting, however, that there was an exception over Florida, "where activity decreased during the early 1950s and again during the late 1960s." Last, they found that "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

In contradiction of the IPCC's claim that global warming leads to more intense hurricane activity, the results of Elsner *et al*.'s study found that not only did North Atlantic hurricane activity not increase over the entire twentieth century, hurricane activity also did not increase in response to the more sporadic warming associated with periodic El Niño conditions.

Two years later, things got a bit more interesting. "The 2005 hurricane season," in the words of Virmani and Weisberg (2006), "saw an unprecedented number of named tropical storms since records began in 1851." Moreover, they said it followed "on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path." The question they thus posed was whether these things occurred in response to recent global warming or if they bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

The two researchers determined that "latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea-level pressure," which phenomenon "resulted in anomalously high sea surface temperatures" that "contributed to earlier and more intense hurricanes in 2005." However, they went on to note that "these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998." In addition, they said there was "not a clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation."

The following year, Mann and Emanuel (2006) used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871-2005, while Holland and Webster (2007) had analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both of these papers linked these changes to anthropogenic greenhouse warming. In a compelling rebuttal of those conclusions, however, Landsea (2007) cited a number of possible biases that may exist in the cyclone frequency trends derived in the two studies, concluding that "improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones."

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

Lupo *et al.* (2008) added data for seven more years to the data originally analyzed by Lupo and Johnston (2000) and found it "did not change the major findings." The authors hypothesized that the Atlantic hurricane season of 2005 was so active, not only because of the recent increase in hurricane activity which may be associated with the PDO, but also possibly due to decreased upper tropospheric shear over the Atlantic which may have been associated with a stronger easterly phase of the quasi-biennial oscillation along with warmer-than-normal SSTs.

In light of the long history of multi-decadal to century-scale analyses that have come to the same conclusion, we must reject the oft-heard claim that Atlantic hurricanes have increased in frequency in response to twentieth century global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlangwe.php.

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6.3.1.2.4. The El Niño Effect

How does the frequency of Atlantic basin hurricanes respond to increases in ocean temperature? In exploring this important question one has to look not only at Atlantic Ocean temperatures, but also those in the eastern tropical Pacific, in particular during La Niña and El Niño conditions. Wilson (1999) utilized data from the last half of the twentieth century to determine that the probability of having three or more intense Atlantic hurricanes was only 14 percent during an El Niño year (warm temperatures in the eastern tropical Pacific), but fully 53 percent during a La Niña year (cold ocean temperatures in the eastern tropical Pacific). When ocean temperatures warm in the eastern tropical Pacific, they cause stronger upper level winds in the tropical Atlantic and a greater likelihood that storms would become sheared, and hence weaker. The opposite (weaker upper level winds) occurs during La Niña years.

Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone, the average rate of strike occurrence ranged from 1.7 per La Niña season to 0.5 per El Niño season, which represents a frequency-of-occurrence decline of fully 70 percent in going from cooler La Niña conditions to warmer El Niño conditions. Likewise, Elsner *et al*. (2001)—who also worked with data from the entire past century—found that when there are below normal sea surface temperatures in the equatorial Pacific, "the probability of a U.S. hurricane increases."

Lyons (2004) also conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three different groupings: the 10 highest storm and hurricane landfall years, the nine lowest such years, and all other years. These groupings revealed, in Lyons' words, that "La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years," and that "El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years." In addition, it was determined that "La Niña (El Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years."

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. In their analysis, they first determined that 22 years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. Then, they compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a 10-year study of a Mediterranean waterbird (Cory's Shearwater) carried out on the other side of the Atlantic, Brichetti *et al*. (2000) determined—contrary to their own expectation—that survival rates during warmer El Niño years were greater than during cooler La Niña years.

In another pertinent study, Landsea *et al*. (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991-94) that had exhibited the lowest such activity since the keeping of reliable records began. They determined that the most important factor behind this dramatic transition from extreme low to extreme high tropical storm and hurricane activity was what they called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions."

Last, in a twentieth century changepoint analysis of time series of major North Atlantic and U.S. annual hurricane counts, which in the words of its authors, "quantitatively identifies temporal shifts in the mean value of the observations," Elsner *et al*. (2004) found that "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanelnino.php.

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6.3.2. Indian Ocean

Singh *et al*. (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877-1998. Since this was the period of time during which the planet recovered from the global chill of the Little Ice Age, it is logical to assume that their findings would be indicative of changes in hurricane characteristics we might expect if the earth were to warm by that amount again, which is what the IPCC is projecting.

Singh *et al*. found that on an annual basis, there was a slight decrease in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one less hurricane per year at the end of the 122-year record in 1998 than it did at its start in 1877. In addition, based on data from the Bay of Bengal, they found that tropical cyclone numbers dropped during the months of most severe cyclone formation (November and May), when the El Niño-Southern Oscillation was in a warm phase. In light of these real-world observations, it would thus appear that if tropical cyclones of the North Indian Ocean were to change at all in response to global warming, their overall frequency and the frequency of the most intense such storms would likely decrease.

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, Hall determined that "the overall number of depressions and tropical cyclones was below the long-term mean." Further east, he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." What is more, Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was by far the quietest recorded in the past 41 years."

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world, giving special attention to the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report that for the period 1891-1997 there was a significant decreasing trend (at the 99 percent confidence level) in the frequency of cyclones with the designation of "cyclonic storm" and above, and that "the maximum decrease was in the last four decades," citing the work of Srivastava *et al*. (2000). In addition, they note that Singh and Khan (1999), who studied 122 years of data, also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

As in other parts of the world, they found increasing impacts of tropical cyclones; but their economic analysis led them to conclude that "increasing damage due to tropical cyclones over Andhra Pradesh, India, is attributable mainly to economic and demographic factors and not to any increase in frequency or intensity of cyclones." With no equivocation, they state that "inflation, growth in population, and the increased wealth of people in the coastal areas (and not global warming) are the factors contributing to the increased impact."

Commenting on their findings, the researchers say "there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change." However, as they continue, "studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones." They confidently state that "the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular media and even in some more serious publications, does not therefore have a sound scientific basis."

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricaneindian.php.

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6.3.3. Pacific Ocean

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that either originated in or entered the central North Pacific (0-70°N, 140-180°W) over the 32-year period 1966-1997. They determined that "tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise." This increase, however, appears to have been due to a step-change that led to the creation of "fewer cyclones during the first half of the record (1966-81) and more during the second half of the record (1982-1997)," and accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity. Chu and Clark say the observed increase in tropical cyclone activity cannot be due to CO_2-induced global warming, because, in their words, "global warming is a gradual process" and "it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s."

Clearly, a much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark, as well as their relationship to mean global air temperature. The beginnings of such a history were presented by Liu *et al*. (2001), who meticulously waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975. Calibrating the historical data against instrumental observations over the period 1884-1909, they found the trends of the two datasets to be significantly correlated (r = 0.71). This observation led them to conclude that "the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls." They proceeded to conduct a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that "suggests an external forcing mechanism, which remains to be identified." They also found that "the two periods of most frequent typhoon strikes in Guangdong (AD 1660-1680, 1850-1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age."

Looking even further back in time into the Southern Hemisphere, Hayne and Chappell (2001) studied a series of storm ridges at Curacoa Island, which were deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events that have impacted that area. One of their stated reasons for doing so was to test the climate-model-based hypothesis that "global warming leads to an increase of cyclone frequency or intensity." They found that "cyclone frequency was statistically constant over the last 5,000 years." In addition, they could find "no indication that cyclones have changed in intensity," a finding that is inconsistent with the climate-model-based hypothesis.

In a similar study, Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S by geologically dating and tropographically surveying landform features left by historic hurricanes, and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed that several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred over the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of their study. They also report that the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The twentieth century, however, was *totally devoid* of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

Also noting that "many researchers have suggested that the buildup of greenhouse gases (Watson *et al*., 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs)," Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data. As they put it, "if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades." Their efforts, which focused on the last four decades of the twentieth century, resulted in their finding that a number of parameters related to SST and TC activity in the Western North Pacific (WNP) "have gone through large interannual as well as interdecadal variations," and that "they also show a slight decreasing trend." In addition, they say that "no significant correlation was found between the typhoon activity parameters and local SST," and "an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models." Instead, they found that "the interannual variation of annual typhoon activity is mainly constrained by the ENSO phenomenon through the alteration of the large-scale circulation induced by the ENSO event."

In discussing their results, Chan and Liu write that the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere. "In other words," as they say, "the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999)," whereas "in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process." Their final conclusion is that "at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs."

Much the same thing was found by Free *et al*. (2004), who looked for increases in potential hurricane intensity, as they put it, "estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." This they did using radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific and Atlantic Oceans, after which they compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This analysis indicated that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, he writes that "the overall number of depressions and tropical cyclones was below the long-term mean," while further east he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was by far the quietest recorded in the past 41 years."

Noting that "according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones," and realizing that "understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events," Yu *et al*. (2004) devised a way to decipher the history of severe storms in the southern South China Sea. Working at Youngshu Reef (9°32'-9°42'N, 112°52 -113°04'E), they used standard radiocarbon dating together with TIMS U-series dating to determine the times of occurrence of storms that were strong enough to relocate large *Porites* coral blocks that are widespread on the reef flats there. This program revealed that "during the past 1000 years, at least six exceptionally strong storms occurred," which they dated to approximately AD 1064 ± 30, 1218 ± 5, 1336 ± 9, 1443 ± 9, 1682 ± 7, and 1872 ± 15, yielding an average recurrence time of 160 years. Interestingly, none of these six severe storms occurred during the past millennium's last century, which the IPCC claims was the warmest such period of that thousand-year interval.

Noting that Emanuel (2005) and Webster *et al*. (2005) have claimed that "tropical cyclone intensity has increased markedly in recent decades," and saying that because they specifically argued that "tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming," Ren *et al*. (2006) decided to see if any increases in tropical cyclone activity had occurred over China between 1957 and 2004. This they did by analyzing tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced torrential precipitation events. This search indicated, in their words, that "significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years." Also, they say that the downward trends were accompanied by "decreases in the numbers of TCs and typhoons that affected China during the period 1957-2004." In a conclusion that consequently differs dramatically from the claims of Emanuel (2005) and Webster *et al*. (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al*. say their findings "strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP."

Nott *et al*. (2007) developed a 777-year-long annually resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. Perhaps their most important discovery in doing so was their finding that "the period between AD 1600 to 1800"—when the Little Ice Age held sway throughout the world—"had many more intense or hazardous cyclones impacting the site than the post AD 1800 period," when the planet gradually began to warm.

Li *et al*. (2007) analyzed real-world tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949-2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951-2003. Following this endeavor, they used their empirical findings to infer future tropical cyclone activity in the region based upon climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed, first, that there were "more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present." They further found that "the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones." Based on simulations of future occurrences of these favorable and unfavorable conditions derived from "a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios," they then determined that "the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it."

Last, an analysis by Lupo *et al*. (2008) of 69 years of East Pacific tropical cyclone activity (1970 – 2007) found that there were 16.3 storms per year (9.0 hurricanes and 7.3 tropical storms), which was a greater amount of activity than found in the Atlantic Ocean basin. The long-term trend showed a slight decrease (not statistically significant) in East Pacific tropical cyclone activity. An examination of the interannual variability demonstrated that there were more East Pacific tropical cyclones during El Niño years, and that this was mainly accounted for by more storms becoming intense hurricanes than during La Niña years. The tropical cyclone season was one or two months longer in El Niño years, while more storms formed in the southeast and southwest part of the East Pacific Ocean Basin. This is likely due to the fact that ENSO years bring warmer waters to the East Pacific region. When breaking down the ENSO years by phase of the PDO, the ENSO-related differences in occurrence and intensity and geographic formation region are accentuated in PDO1 years (1977-1999), but were blurred in PDO2 (1947-1976) years. This ENSO and PDO related variability is similar to that occurring in the Atlantic (LJ00), except that in the Atlantic more storms occurred in La Niña years and they were more intense.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricanepacific.php.

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6.3.4. Global

Although some climate models suggest the intensity and frequency of tropical cyclones on a global scale may be significantly reduced in response to global warming (Bengtsson *et al*., 1996), thus implying a "decrease in the global total number of tropical cyclones on doubling CO_2," as noted by Sugi *et al*. (2002), most of them suggest otherwise. Free *et al*. (2004) state that "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998)."

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) concluded that "the effect of global warming on the number of tropical cyclones is presently unknown," and "there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe." They opined there was "little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers."

In a second early analysis of the topic, Henderson-Sellers *et al*. (1998) determined that (1) "there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses," (2) "global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill," and (3) "the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy."

Six years later, Free *et al*. (2004) looked for increases in "potential" hurricane intensity and found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

In another review of what real-world data have to say about the subject, Walsh (2004) was once again forced to report "there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming." Nevertheless, Walsh continued to believe that (1) "there is likely to be some increase in maximum tropical cyclone intensities in a warmer world," (2) "it is probable that this would be accompanied by increases in mean tropical cyclone intensities," and (3) "these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%," putting the date of possible detection of these increases "some time after 2050," little knowing that two such claims would actually be made the very next year.

Emanuel (2005) claimed to have found that a hurricane power dissipation index had increased by approximately 50 percent for both the Atlantic basin and the Northwest Pacific basin since the mid 1970s, and Webster *et al*. (2005) contended the numbers of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975-1989) and a more recent (1990-2004) 15-year period. However, in a challenge to both of these claims, Klotzbach (2006) wrote that "many questions have been raised regarding the data quality in the earlier part of their analysis periods," and he thus proceeded to perform a new analysis based on a "near-homogeneous" global dataset for the period 1986-2005.

Klotzbach first tabulated global tropical cyclone (TC) activity using best track data—which he describes as "the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers"—for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian, and South Pacific), after which he determined trends of worldwide TC frequency and intensity over the period 1986-2005, during which time global SSTs are purported to have risen by about 0.2-0.4°C. This work did indeed indicate, in his words, "a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin," but it also indicated "a considerable decreasing trend for the Northeast Pacific." Combining these observations with the fact that "all other basins showed small trends," he determined there had been "no significant change in global net tropical cyclone activity" over the past two decades. With respect to Category 4 and 5 hurricanes, however, he found there had been a "small increase" in their numbers from the first half of the study period (1986-1995) to the last half (1996-2005); but he noted that "most of this increase is likely due to improved observational technology." Klotzbach said his findings were "contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al*. (2005)," in that the global TC data did "not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years."

Following close on the heels of Klotzbach's study came the paper of Kossin *et al*. (2007), who wrote that "the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous," and stated that this "known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates." Consequently, as an important first step in resolving this problem, Kossin *et al*. "constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates," after which they analyzed the resultant homogenized data for temporal trends over the period 1984-2004 for all major ocean basins and the global ocean as a whole.

The five scientists who conducted the work said that "using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic." Therefore, noting that "the Atlantic basin accounts for less than 15% of global hurricane activity," they concluded that "this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity." They deliver another major blow to the contentions of Emanuel (2005) and Webster *et al*. (2005) when they say "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future."

As a result of the many investigations of the subject that have been conducted over the past several years, there currently appears to be no factual basis for claiming that planet-wide hurricane frequency and/or intensity will rise in response to potential future global warming. Nevertheless, parties pushing for restrictions on anthropogenic CO_2 emissions continue to do so, citing the now-rebutted claims of Emanuel (2005) and Webster *et al*. (2005).

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricaneglobal.php.

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6.4. ENSO

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. Here, we test the validity of these assertions, demonstrating they are in conflict with the observational record. We begin by highlighting studies that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality.

Additional information on this topic, including reviews on ENSO not discussed here, can be found at http://www.co2science.org/subject/e/subject_e.php under the heading ENSO.

6.4.1. Model Inadequacies

In a comparison of 24 coupled ocean-atmosphere climate models, Latif *et al*. (2001) report that "almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology." They also note that "only a few of the coupled models simulate the El Niño/Southern Oscillation (ENSO) in terms of gross equatorial SST anomalies realistically." And they state that "no model has been found that simulates realistically all aspects of the interannual SST variability." Because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising that Fedorov and Philander (2000) conclude that current climate models do not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also plays a role in the models' failure to simulate ENSO. According to Overpeck and Webb (2000), there is evidence that "ENSO may change in ways that we do not yet understand," which "ways" have clearly not yet been modeled. White *et al*. (2001), for example, found that "global warming and cooling during earth's internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance," and that these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) make a case for a lunar forcing of ENSO activity, which also is not included in any climate model.

Another example of the inability of today's most sophisticated climate models to properly describe El Niño events is provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997-98 El Niño. They found that the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from 0 to eight months. They also determined that no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium range lead-time of six to 11 months. They state that "since no models were able to provide useful predictions at the medium and long ranges, *there were no models that provided both useful and skillful forecasts for the entirety of the 1997-98 El Niño*" [italics in the original].

Given the inadequacies listed above, it is little wonder several scientists have criticized model simulations of current ENSO behavior, including Walsh and Pittock (1998), who say "there is insufficient confidence in the predictions of current models regarding any changes in ENSO," and Fedorov and Philander (2000), who say "at this time, it is impossible to decide which, if any, are correct." As a result, there is also little reason to believe that current climate models can correctly predict ENSO behavior under future conditions of changed climate.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/e/ensomo.php.

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6.4.2. Relationship to Extreme Weather

Changnon (1999) determined that adverse weather events attributed to the El Niño of 1997-98 negatively affected the United States economy to the tune of $4.5 billion and contributed to the loss of 189 lives, which is serious indeed. On the other hand, he determined that El Niño-related benefits amounted to approximately $19.5 billion—resulting primarily from reduced energy costs, increased industry sales, and the lack of normal hurricane damage—and that a total of 850 lives were *saved* due to the reduced amount of bad winter weather. Thus, the net effect of the 1997-98 El Niño on the United States, according to Changnon, was "surprisingly positive," in stark contrast to what was often reported in the media and by some commentators who tend, in his words, "to focus only on the negative outcomes."

Another of the "surprisingly positive" consequences of El Niños is their tendency to moderate Atlantic hurricane frequencies. Working with data from 1950 to 1998, Wilson (1999) determined that the probability of having three or more intense hurricanes during a warmer El Niño year was approximately 14 percent, while during a cooler non-El Niño year the probability jumped to 53 percent. Similarly, in a study of tropical storm and hurricane strikes along the southeast coast of the United States over the entire last century, Muller and Stone (2001) determined that "more tropical storm and hurricane events can be anticipated during La Niña seasons [3.3 per season] and fewer during El Niño seasons [1.7 per season]." And in yet another study of Atlantic basin hurricanes, this one over the period 1925 to 1997, Pielke and Landsea (1999) reported that average hurricane wind speeds during warmer El Niño years were about six meters per second lower than during cooler La Niña years. In addition, they reported that hurricane damage during cooler La Niña years was twice as great as during warmer El Niño years. These year-to-year variations thus indicate that, if anything, hurricane frequency and intensity—as well as damage—tend to decrease under warmer El Niño conditions.

Much the same story is being said of other parts of the world. In the North Indian Ocean, Singh *et al*. (2000) studied tropical cyclone data pertaining to the period 1877-1998, finding that tropical cyclone frequency there declined during the months of most severe cyclone formation—November and May—when ENSO was in a warm phase. In New Zealand, De Lange and Gibb (2000) studied storm surge events recorded by several tide gauges in Tauranga Harbor over the period 1960-1998, finding a considerable decline in both the annual number of such events and their magnitude in the latter (warmer) half of the nearly four-decade-long record, additionally noting that La Niña seasons typically experienced more storm surge days than El Niño seasons. And in Australia, Kuhnel and Coates (2000) found that over the period 1876-1991, yearly fatality event-days due to floods, bushfires, and heatwaves were greater in cooler La Niña years than in warmer El Niño years.

Zuki and Lupo (2008), when examining Southern South China Sea (SSCS) data on tropical storms and cyclones for interannual variability, found La Niña years were more active and El Niño years were less active than other years, and this result was significant at the 95 percent confidence level when examining the total sample. The variability of tropical storms and tropical cyclones of local origin was similar to that of the total sample. There was no apparent climatic variability (statistically significant) in the SSCS that could be attributed to interdecadal variability such as the PDO. A spectral analysis of the filtered climatological background variables such as SST, SLP, 200–850 hPa wind shear, 850 hPa divergence and 850 hPa vorticity showed that there was significant variability found in the 3–7 year period, which is consistent with that of the ENSO period.

Zuki and Lupo then examined a subset of the most active years (all La Niña and ‘‘cold’’ neutral years) versus those years with no tropical cyclone activity for the five years of warmest SSTs (predominantly El Niño years) and coolest SSTs. They found that during warm non-active SST years, tropical cyclone activity was likely suppressed as the low-level relative vorticity was considerably more anticyclonic, even though SSTs were about one standard deviation warmer and wind shears were similar to those of active years. The SSCS atmospheric environment for warm SST non-active years was drier than that of the active years, and did not exhibit a surface–500 hPa structure that would be as supportive of warm-core tropical cyclones. Most of these years were also ENSO years, and two thirds of all years with no activity were El Nino or warm neutral.

Apparently, even birds seem to know the dangers of La Niña vs. El Niño. In a study of breeding populations of Cory’s Shearwaters on the Tremiti Islands of Italy, for example, Brichetti *et al*. (2000) found that, contrary to even their hypothesis, survival rates during El Niño years were greater than during La Niña years.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/e/ensoew.php.

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6.4.3. Relationship to Global Warming

All of the claims regarding the influence of global warming on ENSO events are derived from climate model simulations. Timmermann *et al*. (1999), for example, developed a global climate model which, according to them, operates with sufficient resolution to address the issue of whether “human-induced ‘greenhouse’ warming affects, or will affect, ENSO.” When running this model with increasing greenhouse-gas concentrations, more frequent El-Niño-like conditions do indeed occur. However, this is not what observational data reveal to be the case. The frequent and strong El Niño activity of the recent past is no different from that of a number of other such episodes of prior centuries, when it was colder than it is today, as described in several of the papers highlighted below. And in many instances, the El Niño activity of the recent past is shown to be inferior to that of colder times.

Evans *et al*. (2002) reconstructed gridded Pacific Ocean sea surface temperatures from coral stable isotope ($\delta^{18}O$) data, from which they assessed ENSO activity over the period 1607-1990. The results of their analysis showed that a period of relatively vigorous ENSO activity over the colder-than-present period of 1820-1860 was "similar to [that] observed in the past two decades." Likewise, in a study that was partly based upon the instrumental temperature record for the period 1876-1996, Allan and D'Arrigo (1999) found four persistent El Niño sequences similar to that of the 1990s; using tree-ring proxy data covering the period 1706 to 1977, they found several other ENSO events of prolonged duration. There were four or five persistent El Niño sequences in each of the eighteenth and nineteenth centuries, which were both significantly colder than the final two decades of the twentieth century, leading them to conclude there is "no evidence for an enhanced greenhouse influence in the frequency or duration of 'persistent' ENSO event sequences."

Brook *et al*. (1999) analyzed the layering of couplets of inclusion-rich calcite over inclusion-free calcite, and darker aragonite over clear aragonite, in two stalagmites from Anjohibe Cave in Madagascar, comparing their results with historical records of El Niño events and proxy records of El Niño events and sea surface temperatures derived from ice core and coral data. This exercise revealed that the cave-derived record of El Niño events compared well with the historical and proxy ice core and coral records; these data indicated, in Brook *et al*.'s words, that "the period 1700-50 possibly witnessed the highest frequency of El Niño events in the last four and a half centuries while the period 1780-1930 was the longest period of consistently high El Niño occurrences," both of which periods were cooler than the 1980s and 1990s.

In another multi-century study, Meyerson *et al*. (2003) analyzed an annually dated ice core from the South Pole that covered the period 1487-1992, specifically focusing on the marine biogenic sulfur species methanesulfonate (MS), after which they used orthogonal function analysis to calibrate the high-resolution MS series with associated environmental series for the period of overlap (1973-92). This procedure allowed them to derive a five-century history of ENSO activity and southeastern Pacific sea-ice extent, the latter of which parameters they say "is indicative of regional temperatures within the Little Ice Age period in the southeastern Pacific sea-ice sector."

In analyzing these records, Meyerson *et al*. noted a shift at about 1800 towards generally cooler conditions. This shift was concurrent with an increase in the frequency of El Niño events in the ice core proxy record, which is contrary to what is generally predicted by climate models. On the other hand, their findings were harmonious with the historical El Niño chronologies of both South America (Quinn and Neal, 1992) and the Nile region (Quinn, 1992; Diaz and Pulwarty, 1994), which depict, in their words, "increased El Niño activity during the period of the Little Ice Age (nominally 1400-1900) and decreased El Niño activity during the Medieval Warm Period (nominally 950-1250)," as per Anderson (1992) and de Putter *et al*., 1998).

Taking a little longer look back in time were Cobb *et al*. (2003), who generated multi-century monthly resolved records of tropical Pacific climate variability over the last millennium by splicing together overlapping fossil-coral records from the central tropical Pacific, which exercise allowed them "to characterize the range of natural variability in the tropical Pacific climate system with unprecedented fidelity and detail." In doing so, they discovered that "ENSO activity in the seventeenth-century sequence [was] not only stronger, but more frequent than ENSO activity in the late twentieth century." They also found "there [were] 30-yr intervals during both the twelfth and fourteenth centuries when ENSO activity [was] greatly reduced relative to twentieth-century observations." Once again, we have evidence of a situation where ENSO activity was much greater and more intense during the cold of the Little Ice Age than the warmth of the late twentieth century.

Inching still further back in time, Eltahir and Wang (1999) used water-level records of the Nile River as a proxy for El Niño episodes over the past 14 centuries. This approach indicated that although the frequency of El Niño events over the 1980s and 1990s was high, it was not without precedent, being similar to values observed near the start of the twentieth century and much the same as those "experienced during the last three centuries of the first millennium," which latter period, according to Esper *et al*. (2002), was also cooler than the latter part of the twentieth century.

Woodroffe *et al*. (2003) found pretty much the same thing, but over an even longer period of time. Using oxygen isotope ratios obtained from *Porites* microatolls at Christmas Island in the central Pacific to provide high-resolution proxy records of ENSO variability since 3.8 thousand years ago (ka), they found, in their words, that "individual ENSO events in the late Holocene [3.8-2.8 ka] appear at least as intense as those experienced in the past two decades." In addition, they note that "geoarcheological evidence from South America (Sandweiss *et al*., 1996), Ecuadorian varved lake sediments (Rodbell *et al*., 1999), and corals from Papua New Guinea (Tudhope *et al*., 2001) indicate that ENSO events were considerably weaker or absent between 8.8 and 5.8 ka," which was the warmest part of the Holocene. In fact, they report that "faunal remains from archeological sites in Peru (Sandweiss *et al*., 2001) indicate that the onset of modern, rapid ENSO recurrence intervals was achieved only after ~4-3 ka," or during the long cold interlude that preceded the Roman Warm Period (McDermott *et al*., 2001).

Also concentrating on the mid to late Holocene were McGregor and Gagan (2004), who used several annually resolved fossil *Porites* coral $\delta^{18}O$ records to investigate the characteristics of ENSO events over a period of time in which the earth cooled substantially. For comparison, study of a modern coral core provided evidence of ENSO events for the period 1950-1997, the results of which analysis suggest they occurred at a rate of 19 events/century. The mid-Holocene coral $\delta^{18}O$ records, on the other hand, showed reduced rates of ENSO occurrence: 12 events/century for the period 7.6-7.1 ka, eight events/century for the period 6.1-5.4 ka, and six events/century at 6.5 ka. For the period 2.5-1.7 ka, however, the results were quite different, with all of the coral records revealing, in the words of McGregor and Gagan, "large and protracted $\delta^{18}O$ anomalies indicative of particularly severe El Niño events." They note specifically that "the 2.5 ka Madang PNG coral records a protracted 4-year El Niño, like the 1991-1994 event, but almost twice the amplitude of [the] 1997-1998 event (Tudhope *et al*., 2001)." In addition, they say that "the 2 ka Muschu Island coral $\delta^{18}O$ record shows a severe 7-year El Niño, longer than any recorded Holocene or modern event." And they add that "the 1.7 ka *Porites* microatoll of Woodroffe *et al*. (2003) also records an extreme El Niño that was twice the amplitude of the 1997-1998 event." Taken together, these several sets of results portray what McGregor and Gagan describe as a "mid-Holocene El Niño suppression and late Holocene amplification."

That there tend to be fewer and weaker ENSO events during warm periods has further been documented by Riedinger *et al*. (2002). In a 7,000-year study of ENSO activity in the vicinity of the Galapagos Islands, they determined that "mid-Holocene [7,130 to 4,600 yr BP] El Niño activity was infrequent," when, of course, global air temperature was significantly warmer than it is now, but that both the "frequency and intensity of events increased at about 3100 yr BP," when it finally cooled below current temperatures. Throughout the former 2,530-year warm period, their data revealed the existence of 23 strong to very strong El Niños and 56 moderate events; while throughout the most recent (and significantly colder) 3,100-year period, they identified 80 strong to very strong El Niños and 186 moderate events. These numbers correspond to rates of 0.9 strong and 2.2 moderate occurrences per century in the earlier warm period and 2.7 strong and 6.0 moderate occurrences per century in the latter cool period, suggestive of an approximate tripling of the rate of occurrence of both strong and moderate El Niños in going from the warmth of the Holocene "Climatic Optimum" to the colder conditions of the past three millennia.

Similar results have been reported by Andrus *et al*. (2002) and Moy *et al*. (2002). According to Andrus *et al*., sea surface temperatures off the coast of Peru some 6,000 years ago were 3° to 4°C warmer than what they were over the decade of the 1990s and provided little evidence of any El Niño activity. Nearby, Moy *et al*. analyzed a sediment core from lake Laguna Pallcacocha in the southern Ecuadorian Andes, producing a proxy measure of ENSO over the past 12,000 years. For the moderate and strong ENSO events detected by their analytical techniques (weaker events are not registered), these researchers state that "the overall trend exhibited in the Pallcacocha record includes a low concentration of events in the early Holocene, followed by increasing occurrence after 7,000 cal. yr BP, with peak event frequency occurring at ~1,200 cal. yr BP," after which the frequency of events declines dramatically to the present.

With respect to the last 1,200 years of this record, the decline in the frequency of ENSO events is anything but smooth. In coming out of the Dark Ages Cold Period, which was one of the coldest intervals of the Holocene (McDermott *et al*., 2001), the number of

ENSO events experienced by the earth drops by an order of magnitude, from a high of approximately 33 events per 100 yr to a low of about three events per 100 yr, centered approximately on the year AD 1000, which is right in the middle of the Medieval Warm Period, as delineated by the work of Esper *et al*. (2002). Then, at approximately AD 1250, the frequency of ENSO events exhibits a new peak of approximately 27 events per 100 yr in the midst of the longest sustained cold period of the Little Ice Age, again as delineated by the work of Esper *et al*. Finally, ENSO event frequency declines in zigzag fashion to a low on the order of four to five events per 100 yr at the start of the Current Warm Period, which according to the temperature history of Esper *et al*. begins at about 1940.

Going even further back in time, in a study of a recently revised New England varve chronology derived from proglacial lakes formed during the recession of the Laurentide ice sheet some 17,500 to 13,500 years ago, Rittenour *et al*. (2000) determined that "the chronology shows a distinct interannual band of enhanced variability suggestive of El Niño-Southern Oscillation (ENSO) teleconnections into North America during the late Pleistocene, when the Laurentide ice sheet was near its maximum extent ... during near-peak glacial conditions." But during the middle of the Holocene, when it was considerably warmer, even than it is today, Overpeck and Webb (2000) report that data from corals suggest that "interannual ENSO variability, as we now know it, was substantially reduced, or perhaps even absent."

In summing up the available evidence pertaining to the effect of temperature on the frequency of occurrence and strength of ENSO events, we have one of the most sophisticated climate models ever developed to deal with the ENSO phenomenon implying that global warming will promote more frequent El Niño-like conditions. But we also have real-world observations demonstrating that El Niño-like conditions during the latter part of the twentieth century (claimed by the IPCC to be the warmest period of the past 1,300 years) are not much different from those that occurred during much colder times. In addition, we have a number of long-term records that suggest that when the earth was significantly warmer than it is currently, ENSO events were substantially reduced or perhaps even absent.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/e/ensogw.php.

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6.5. Precipitation Variability

The IPCC contends that global warming is responsible for causing greater variability in precipitation, leading to more droughts and floods. In this section we review empirical research on precipitation patterns in Africa, Asia, and North America.

Additional information on this topic, including reviews on precipitation not discussed here, can be found at http://www.co2science.org/subject/p/subject_p.php under the heading Precipitation.

6.5.1. Africa

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

As the Little Ice Age's grip on the world began to loosen in the mid to latter part of the 1800s, however, things began to improve for most of the continent. Nicholson and Yin report that "semi-arid regions of

Mauritania and Mali experienced agricultural prosperity and abundant harvests ... the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region." Across the length of the northern Sahel, maps and geographical reports described the presence of "forests." As the nineteenth century came to an end and the twentieth century began, there was a slight lowering of lake levels, but nothing like what had occurred a century earlier (i.e., variability was much reduced). And then, in the latter half of the twentieth century, things once again began to pick up for the Africans, with the levels of some of the lakes rivaling the high-stands characteristic of the years of transition to the Current Warm Period.

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

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

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

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

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/p/variabilafrica.php.

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6.5.2. Asia

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

Kripalani and Kulkarni (2001) studied seasonal summer monsoon (June-September) rainfall data from 120 east Asia stations for the period 1881-1998. A series of statistical tests they applied to these data revealed the presence of short-term variability in rainfall amounts on decadal and longer time scales, the longer "epochs" of which were found to last for about three decades over China and India and for approximately five decades over Japan. With respect to long-term trends, however, none was detected. Consequently, the history of summer rainfall trends in east Asia does not support claims of intensified monsoonal conditions in this region as a result of CO_2-induced global warming. As for the decadal variability inherent in the record, the two researchers say it "appears to be just a part of natural climate variations."

Taking a much longer look at the Asian monsoon were Ji *et al*. (2005), who used reflectance spectroscopy on a sediment core taken from a lake in the northeastern part of the Qinghai-Tibetan Plateau to obtain a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. This project indicated that monsoonal moisture since the late glacial period had been subject to "continual and cyclic variations," among which was a "very abrupt onset and termination" of a 2,000-year dry spell that started about 4,200 years ago (yr BP) and ended around 2,300 yr BP. Other variations included the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age (LIA), which lasted from 2,100 yr BP to 1,800 yr BP and 780 yr BP to 400 yr BP, respectively, while sandwiched between them was the warmer and wetter Medieval Warm Period, and preceding the DACP was the Roman Warm Period. Time series analyses of the sediment record also revealed several statistically significant periodicities (123, 163, 200, and 293 years, all above the 95 percent level), with the 200-year cycle matching the de Vries or Suess solar cycle, implying that changes in solar activity are important triggers for some of the recurring precipitation changes in that part of Asia. It is clear that large and abrupt fluctuations in the Asian monsoon have occurred numerous times and with great regularity throughout the Holocene, and that the sun played an important role in orchestrating them.

Also working on the Tibetan Plateau were Shao *et al*. (2005), who used seven Qilian juniper ring-width chronologies from the northeastern part of the Qaidam Basin to reconstruct a thousand-year history of annual precipitation there. In doing so, they discovered that annual precipitation had fluctuated at various intervals and to various degrees throughout the entire past millennium. Wetter periods occurred between 1520 and 1633, as well as between 1933 and 2001, although precipitation has declined somewhat since the 1990s. Drier periods, on the other hand, occurred between 1429 and 1519 and between 1634 and 1741. With respect to variability, the scientists report that the magnitude of variation in annual precipitation was about 15 mm before 1430, increased to 30 mm between 1430 and 1850, and declined thereafter to the present.

Based on analyses of tree-ring width data and their connection to large-scale atmospheric circulation, Touchan *et al*. (2005) developed summer (May-August) precipitation reconstructions for several parts of the eastern Mediterranean region (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back in time anywhere from 115 to 600 years. Over the latter length of time, they found that May-

August precipitation varied on multiannual and decadal timescales, but that on the whole there were no long-term trends. The longest dry period occurred in the late sixteenth century (1591-1595), while there were two extreme wet periods: 1601-1605 and 1751-1755. In addition, both extremely strong and weak precipitation events were found to be more variable over the intervals 1520-1590, 1650-1670, and 1850-1930. The results of this study demonstrate there was nothing unusual or unprecedented about late twentieth century precipitation events in the eastern Mediterranean part of Asia that would suggest a CO_2 influence.

Last, Davi *et al*. (2006) used absolutely dated tree-ring-width chronologies obtained from five sampling sites in west-central Mongolia to derive individual precipitation models, the longest of which stretches from 1340 to 2002, additionally developing a reconstruction of streamflow that extends from 1637 to 1997. In the process of doing so, they discovered there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," which for the region they studied covers the period from 1937 to 2003. In addition, they say their streamflow history indicates that "the wettest 5-year period was 1764-68 and the driest period was 1854-58," while "the most extended wet period [was] 1794-1802 and ... extended dry period [was] 1778-83." For this part of Mongolia, therefore, which the researchers say is "representative of the central Asian region," there is no support to be found for the contention that the "unprecedented warming" of the twentieth century has led to increased variability in precipitation and streamflow.

These several findings suggest that either there is nothing unusual about Asia's current degree of warmth, i.e., it is not unprecedented relative to that of the early part of the past millennium, or unprecedented warming need not lead to unprecedented precipitation or unprecedented precipitation variability ... or both of the above. We conclude that the findings of this study and of others reviewed in this section provide no support for the contention that global warming leads to greater and more frequent precipitation extremes in Asia.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/p/variabilasia.php.

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6.5.3. North America

Cronin *et al*. (2000) studied salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United Sates, in an effort to determine precipitation variability in the surrounding watershed over the prior millennium. They discovered there was a high degree of decadal and multidecadal variability in moisture conditions over the 1,000-year period, with regional precipitation totals fluctuating by between 25 percent and 30 percent, often in extremely rapid shifts occurring over about a decade. They also determined that precipitation was generally greater over the past two centuries than it was over the eight previous centuries, with the exception of a portion of the Medieval Warm Period (AD 1250-1350), when the climate was extremely wet. In addition, they found that the region surrounding Chesapeake Bay had experienced several "mega-droughts" lasting from 60-70 years, some of which the researchers say "were more severe than twentieth century droughts." Likewise, across the continent, Haston and Michaelsen (1997) developed a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies; their work also revealed that "region-wide precipitation during the last 100 years has been unusually high and less variable compared to other periods in the past."

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

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

Dropping down into the Uinta Basin Watershed of northeastern Utah, Gray *et al.* (2004) used cores extracted from 107 piñon pines at four different sites to develop a proxy record of annual (June to June) precipitation spanning the period AD 1226-2001. They report that "single-year dry events before the instrumental period tended to be more severe than those after 1900," and that decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found that "dry events in the late 13th, 16th, and 18th centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900." At the other end of the spectrum, they report that the twentieth century contained two of the strongest wet intervals (1938-1952 and 1965-1987), although the two periods were only the seventh and second most intense wet regimes, respectively, of the entire record. Hence, it would appear that in conjunction with twentieth century global warming, precipitation extremes (both high and low) within the Uinta Basin of northeastern Utah have become attenuated as opposed to amplified.

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

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

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

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/p/variabilnortham.php.

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6.6. Storms

Among the highly publicized changes in weather phenomena that are predicted to attend the ongoing rise in the air's CO_2 content are increases in the frequency and severity of all types of storms. Many researchers have examined historical and proxy records in an attempt to determine how temperature changes over the past millennium or two have affected this aspect of earth's climate. This section reviews what some of them have learned about storm trends, focusing on Europe and North America.

A number of studies have reported increases in North Atlantic storminess over the last two decades of the twentieth century (Jones *et al*., 1997; Gunther *et al*., 1998; Dickson *et al*., 2000). Since the IPCC claims this period was the warmest of the past millennium, this observation might appear to vindicate their view of the subject. When much longer time periods are considered, however, the storminess of the twentieth century is found to be not uncommon and even mild compared to times when temperatures and CO_2 levels were lower.

Dawson *et al*. (2002) searched daily meteorological records from Stornoway (Outer Hebrides), Lerwick (Shetland Islands), Wick (Caithness), and Fair Isle (west of the Shetland Islands) for all data pertaining to gale-force winds over the period 1876-1996, which they used to construct a history of storminess for that period for northern and northwestern Scotland. This history indicated that although North Atlantic storminess and associated wave heights had indeed increased over the prior two decades, storminess in the North Atlantic region "was considerably more severe during parts of the nineteenth century than in recent decades." In addition, whereas the modern increase in storminess appeared to be associated with a spate of substantial positive values of the North Atlantic Oscillation (NAO) index, they say "this was not the case during the period of exceptional storminess at the close of the nineteenth century." During that earlier period, the conditions that fostered modern storminess were apparently overpowered by something even more potent, i.e., cold temperatures, which in the view of Dawson *et al*. led to an expansion of sea ice in the Greenland Sea that expanded and intensified the Greenland anticyclone, which in turn led to the North Atlantic cyclone track being displaced farther south. Additional support for this view is provided by the hypothesis propounded by Clarke *et al*. (2002), who postulated that a southward spread of sea ice and polar water results in an increased thermal gradient between 50°N and 65°N that intensifies storm activity in the North Atlantic and supports dune formation in the Aquitaine region of southwest France.

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

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

Much the same results were obtained by Pirazzoli (2000), who analyzed tide-gauge, wind, and atmospheric pressure data over the period 1951-1997 for the northern portion of the Atlantic coast of France. In that study, the number of atmospheric depressions (storms) and strong surge winds were found to be decreasing in frequency. In addition, it was reported that "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding."

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

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

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

In extending the history of debris-flow events (1922-2002) back to the year 1605, they found that "phases with accentuated activity and shorter recurrence intervals than today existed in the past, namely after 1827 and until the late nineteenth century." What is more, the nineteenth century period of high-frequency debris flow was shown to coincide with a period of higher flood activity in major Swiss rivers, while less frequent debris flow activity after 1922 corresponded with lower flooding frequencies. In addition, debris flows from extremely large mass movement events, similar to what occurred in 1993, were found to have "repeatedly occurred" in the historical past, and to have been of such substantial magnitude that, in the opinion of Stoffel *et al*., the "importance of the 1993 debris-flow surges has to be thoroughly revised." They reported that debris flows occurred "ever more frequently in the nineteenth century than they do today" and concluded that "correlations between global warming and modifications in the number or the size of debris-flow events, as hypothesized by, e.g., Haeberli and Beniston (1998), cannot, so far, be confirmed in the study area."

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

Moving cross-continent to the south and west, Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, to determine historical trends of surges and anomalies. This work revealed that weak and moderate positive surges did not exhibit any definite trends, while strong positive surges clearly became less frequent, even in the face of a gradually rising sea level, "presumably," in the words of Raicich, "as a consequence of a general weakening of the atmospheric activity," which was also found to have been the case for Brittany by Pirazzoli (2000).

Further north, Björck and Clemmensen (2004) extracted cores of peat from two raised bogs in the near-coastal part of southwest Sweden, from which they derived histories of wind-transported clastic material via systematic counts of quartz grains of various size classes that enabled them to calculate temporal variations in Aeolian Sand Influx (ASI), which has been shown to be correlated with winter wind climate in that part of the world. In doing so, they found that "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, they note that "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, that the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they say that an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645-1715)," while further back in time they report high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting that this period coincides with the Sporer Minimum of AD 1420-1530. In addition, they call attention to the fact that the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Last, the two researchers report that degree of humification (DOH) intervals "correlate well with the classic late-Holocene climatic intervals," which they specifically state to include the Modern Climate Optimum (100-0 cal. yr BP), the Little Ice Age (600-100 cal. yr BP), the Medieval Warm Period (1,250-600 cal. yr BP), the Dark Ages Cold Period (1,550-1,250 cal. yr BP) and the Roman Climate Optimum (2,250-1,550 cal. yr BP). There would thus appear to be little doubt that winter storms throughout southern Scandinavia were more frequent and intense during the multi-century Dark Ages Cold Period and Little Ice Age than they were during the Roman Warm Period, the Medieval Warm Period, and the Current Warm Period, providing strong evidence to refute the IPCC's contention that storminess tends to increase during periods of greater warmth. In the real world, just the opposite would appear to be the case.

Also working in Sweden were Barring and von Storch (2004), who say the occurrence of extreme weather events may "create the perception that ... the storms lately have become more violent, a trend that may continue into the future." These two researchers analyzed long time series of pressure readings for Lund (since 1780) and Stockholm (since 1823), analyzing (1) the annual number of pressure observations below 980 hPa, (2) the annual number of absolute pressure tendencies exceeding 16 hPa/12h, and (3) intra-annual 95th and 99th percentiles of the absolute pressure differences between two consecutive observations. They determined that the storminess time series they developed "are remarkably stationary in their mean, with little variations on time scales of more than one or two decades." They note that "the 1860s-70s was a period when the storminess indices showed general higher values," as was the 1980s-90s, but that, subsequently, "the indices have returned to close to their long-term mean."

Barring and von Storch conclude that their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." In fact, during "the entire historical period," in their words, storminess was "remarkably stable, with no systematic change and little transient variability."We can conclude that for much of Sweden, at least, there was no warming-induced increase in windstorms over the entire transitional period between the Little Ice Age and the Current Warm Period.

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

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

Moving over to the United States, Zhang *et al*. (2000) used 10 long-term records of storm surges derived from hourly tide gauge measurements to calculate annual values of the number, duration, and integrated intensity of storms in eastern North America. Their analysis did not reveal any trends in storm activity during the twentieth century, which they say is suggestive of "a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr."

Similar results were found by Boose *et al*. (2001). After scouring historical records to reconstruct hurricane damage regimes for an area composed of the six New England states plus adjoining New York City and Long Island for the period 1620-1997, they could discern "no clear century-scale trend in the number of major hurricanes." For the most recent and reliable 200-year portion of the record, however, the cooler nineteen century had five of the highest-damage category 3 storms, while the warmer twentieth century had only one such storm. Hence, as the earth experienced the warming associated with its recovery from the cold temperatures of the Little Ice Age, it would appear this part of the planet (New England, USA) experienced a decline in the intensity of severe hurricanes.

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

Moving to southern North America, land-falling hurricanes whose eyes crossed the coast between Cape Sable, Florida and Brownsville, Texas between 1896 and 1995 were the subject of investigation by Bove *et al*. (1998). The authors note that the first half of the twentieth century saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. The same holds true for intense hurricanes of category 3 on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes have both been trending downward since 1966, with the decade starting in 1986 exhibiting the fewest intense hurricanes of the century.

Liu and Fearn (1993) also studied major storms along the U.S. Gulf Coast, but over a much longer time period: the past 3,500 years. Using sediment cores taken from the center of Lake Shelby in Alabama they determined that "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years," the last of which super-storms occurred around 700 years ago. They further note that "climate modeling results based on scenarios of greenhouse warming predict a 40%—50% increase in hurricane intensities in response to warmer tropical oceans." If one of these severe storms (which is now about a century overdue) were to hit the Alabama coast again, some commentators would probably cite its occurrence as vindication of the IPCC's doomsday predictions. In reality, it would be the result of natural (not man-made) causes.

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

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

After completing this large regional study, S.A. Changnon (2001) turned his attention to an urban and a more rural site in Chicago in an attempt to determine if there might be an urban heat island influence on thunderstorm activity. Over the 40-year period investigated (1959-1998), he found the urban station experienced an average of 4.5 (12 percent) more thunderstorm days per year than the more rural station; statistical tests revealed this difference to be significant at the 99 percent level in all four seasons of the year. This suggests that the actual decreases in hail- and thunder-days Changnon and Changnon found for the interior of the United States over the last half of the twentieth century may well have been even greater than what they reported in 2000.

Also in the interior of North America, Schwartz and Schmidlin (2002) compiled a blizzard database for the years 1959-2000 for the conterminous United States. A total of 438 blizzards were identified in the 41-year record, yielding an average of 10.7 blizzards per year. Year-to-year variability was significant, with the number of annual blizzards ranging from a low of 1 in the winter of 1980/81 to a high of 27 during the winter of 1996/97. Linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period; but the total area affected by blizzards each winter remained relatively constant and showed no trend. If these observations are both correct, then average blizzard size is much smaller now than it was four decades ago. As the authors note, however, "it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

The results of this study thus suggest that—with respect to U.S. blizzards—frequency may have increased, but if it did, intensity likely decreased. On the other hand, the study's authors suggest that the reported increase in blizzard frequency may well be due to an observational bias that developed over the years, for which there is a known analogue in the historical observation of tornados. For example, Gulev *et al.* (2001) analyzed trends in Northern Hemispheric winter cyclones over essentially the same time period (1958-1999) and found a statistically significant decline of 1.2 cyclones per year using NCEP/NCAR reanalysis pressure data.

Further evidence that the blizzard frequency data are observationally biased can be deduced from the study of Hayden (1999), who investigated storm frequencies over North America between 25° and 55°N latitude and 60° and 125°W longitude from 1885 to 1996. Over this 112-year period, Hayden reports that large regional changes in storm occurrences were observed; but when integrated over the entire geographic area, no net change in storminess was evident.

To the north, Mason and Jordan (2002) studied numerous depositional environments along the tectonically stable, unglaciated eastern Chuckchi Sea coast that stretches across northwest Alaska, deriving a 6,000-year record of sea-level change while simultaneously learning some interesting things about the correlation between storminess and climate in that part of the world. With respect to storminess, they learned that "in the Chukchi Sea, storm frequency is correlated with colder rather than warmer climatic conditions." Consequently, they say that their data "do not therefore support predictions of more frequent or intense coastal storms associated with atmospheric warming for this region."

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

In conclusion, as the earth has warmed over the past 150 years during its recovery from the global chill of the Little Ice Age there has been no significant increase in either the frequency or intensity of stormy weather in Europe and North America. In fact, most studies suggest just the opposite has probably occurred.

Additional information on this topic, including reviews of storms not discussed here, can be found at http://www.co2science.org/subject/s/subject_s.php under the heading Storms.

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6.7. Snow

The IPCC claims “snow cover has decreased in most regions, especially in spring,” and “decreases in snowpack have been documented in several regions worldwide based upon annual time series of mountain snow water equivalent and snow death. (IPCC, 2007-I, p. 43). Later in the report, the authors claim “observations show a global-scale decline of snow and ice over many years, especially since 1980 and increasing during the past decade, despite growth in some places and little change in others” (p. 376). Has global warming really caused there to be less snow? We addressed this question regarding polar regions in Chapters 3 and 4 of this report. In this section, we focus (as the IPCC does) on studies conducted in North America.

Brown (2000) employed data from Canada and the United States to reconstruct monthly snow cover properties over mid-latitude (40-60°N) regions of North America back to the early 1900s, finding evidence of what he described as “a general twentieth century increase in North American snow cover extent, with significant increases in winter (December-February) snow water equivalent averaging 3.9% per decade.” This finding is consistent with climate model simulations that indicate increased precipitation in response to global warming, but it covers too little time to tell us much about the *cause* of increased snow cover.

Moore *et al*. (2002) studied a longer period of time in their analysis of a 103-meter ice core retrieved from a high elevation site on Mount Logan—Canada's highest mountain—which is located in the heavily glaciated Saint Elias region of the Yukon. From this deep core, as well as from some shallow coring and snow-pit sampling, they derived a snow accumulation record that extended over three centuries (from 1693 to 2000), which indicated that heavier snow accumulation at their study site was generally associated with warmer tropospheric temperatures over northwestern North America.

Over the first half of their record, there is no significant trend in the snow accumulation data. From 1850 onward, however, there is a positive trend that is significant at the 95 percent confidence level, which indicates that recovery from the cold conditions of the Little Ice Age began in the mid-1800s, well before there was a large increase in the air's CO_2 concentration. This finding is further strengthened by the temperature reconstruction of Esper *et al*. (2002), which places the start of modern warming at about the same time as that suggested by Moore *et al*.'s snow data, contradicting the temperature record of Mann *et al*. (1998, 1999), which puts the beginning of the modern warming trend at about 1910.

Cowles *et al*. (2002) analyzed snow water equivalent (SWE) data obtained from four different measuring systems—snow courses, snow telemetry, aerial markers, and airborne gamma radiation—at more than 2,000 sites in the 11 westernmost states of the conterminous USA over the period 1910-1998, finding that the long-term SWE trend of the region was negative, indicative of declining winter precipitation. In addition, they report that their results "reinforce more tenuous conclusions made by previous authors," citing Changnon *et al*. (1993) and McCabe and Legates (1995), who studied snow course data from 1951-1985 and 1948-1987, respectively, at 275 and 311 sites, and who also found a decreasing trend in SWE at most sites in the Pacific Northwest.

Schwartz and Schmidlin (2002) examined past issues of *Storm Data*—a publication of the U.S. National Weather Service (NWS)—to compile a blizzard database for the years 1959-2000 for the conterminous United States. This effort resulted in a total of 438 blizzards being identified in the 41-year record, yielding an average of 10.7 blizzards per year; linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period. However, the total *area* affected by blizzards each winter remained relatively constant. If these observations are both correct, average blizzard size must have decreased over the four-decade period. On the other hand, as the researchers note, "it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

In a study of winter weather variability, Woodhouse (2003) generated a tree-ring based reconstruction of SWE for the Gunnison River basin of western Colorado that spans the period 1569-1999. This work revealed, in her words, that "the twentieth century is notable for several periods that lack extreme years." She reports that "the twentieth century is notable for several periods that contain few or no extreme years, for both low and high SWE extremes."

Lawson (2003) examined meteorological records for information pertaining to the occurrence and severity of blizzards within the Prairie Ecozone of western Canada. Over the period 1953-1997, no significant trends were found in central and eastern locations. However, there was a significant *downward* trend in blizzard frequency in the western prairies; Lawson remarks that "this trend is consistent with results found by others that indicate a decrease in cyclone frequency over western Canada." He also notes that the blizzards that do occur there "exhibit no trend in the severity of their individual weather elements." These findings, in his words, "serve to illustrate that the changes in extreme weather events anticipated under Climate Change may not always be for the worse."

Berger *et al.* (2003) collected a 50-year record (1949/1950 to 1998/1999) of snowfall occurrences using data from a dense network of cooperative station observations covering northwest and central Missouri provided by the Missouri Climate Center. The study looked at long-term trends and interannual variability in snowfall occurrence as related to sea surface temperature variations in the Pacific Ocean basin associated with the El Niño and Southern Oscillation (ENSO) and the North Pacific Oscillation (NPO). These trends and variations were then related to four synoptic-scale flow regimes that produce these snowfalls in the Midwest. The authors found no significant long-term trend in overall snowfall occurrence and a decrease in the number of extreme events (≥10 in, >25 cm) was noted. Two years later, Lupo *et al.* (2005) assembled a similar 54-year database (1948/1949 to 2002/2003) of snowfall occurrences for southwest Missouri and found "no variability or trends with respect to longer-term climatic variability and/or climate change."

Bartlett *et al*. (2005) set out to determine what changes might have occurred in the mean onset date of snow and its yearly duration in North America over the period 1950-2002, based on data for the contiguous United States that come from the 1,062 stations of the U.S. Historical Climatology Network, data for Canada that come from the 3,785 stations of the Canadian Daily Climate Dataset, and data for Alaska that come from the 543 stations of the National Weather Service cooperative network in that state. As a result of their efforts, the three researchers found that "for the period 1961-1990 the mean snow onset date in North America [was] 15 December, with mean snow cover duration of 81 days." They report there were "no significant trends in either onset or duration from 1950 to 2002." However, interannual variations of as much as 18 and 15 days in onset and duration, respectively, were present in the data; for both parameters they report that "no net trend was observed."

We find it significant that from 1950 to 2002, during which time the air's CO_2 concentration rose by 20 percent (from approximately 311 to 373 ppm), there was no net change in either the mean onset or duration of snow cover for the entire continent of North America. To provide some context for this 62-ppm increase in atmospheric CO_2 concentration, we note that it is essentially identical to the mean difference between the highs and lows of the three interglacials and glacials reported by Siegenthaler *et al*. (2005) for the period prior to 430,000 years ago. Surely, one would expect that such a change should have had some effect on North American snow cover—unless, of course, atmospheric CO_2 enrichment has very little or no impact on climate.

Julander and Bricco (2006) reported that snowpack data were being consistently used as indicators of global warming, and that individuals doing so should quantify, as best they could, all other influences embedded in their data. That meeting this requirement is no trivial undertaking is indicated by their statement that "snow data may be impacted by site physical changes, vegetation changes, weather modification, pollution, sensor changes, changes in transportation or sampling date, comparisons of snow course to SNOTEL data, changes in measurement personnel or recreational and other factors," including sensors that "do not come back to zero at the end of the snow season." In an analysis of 134 sites (some having pertinent data stretching back to at least 1912), they thus selected 15 long-term Utah snow courses representing complete elevational and geographic coverage of the dominant snowpacks within the state and adjusted them for the major known site conditions affecting the data, after which the adjusted data for the period 1990-2005 were "compared to earlier portions of the historic record to determine if there were statistically significant differences in snowpack characteristics, particularly those that could indicate the impacts of global warming."

Of the 15 sites studied in greatest detail, the two researchers found that seven of them exhibited increased snowpack in recent years, while eight exhibited decreased snow accumulation. They also report that "six of the seven sites with increases have significant vegetative or physical conditions leading us to believe that the impacts associated with this analysis are overstated." The ultimate conclusion of Julander and Bricco, therefore, was that "any signature of global warming currently present in the snowpack data of Utah is not yet at a level of statistical significance ... and will likely be very difficult to isolate from other causes of snowpack decline."

Changnon and Changnon (2006) analyzed the spatial and temporal distributions of damaging snowstorms and their economic losses by means of property-casualty insurance data pertaining to "highly damaging storm events, classed as catastrophes by the insurance industry, during the 1949-2000 period." This work indicated, as they describe it, that "the incidence of storms peaked in the 1976-1985 period," but that snowstorm incidence "exhibited no up or down trend during 1949-2000." The two researchers concluded their paper by stating that "the temporal frequency of damaging snowstorms during 1949-2000 in the United States does not display any increase over time, indicating that either no climate change effect on cyclonic activity has begun, or if it has begun, altered conditions have not influenced the incidence of snowstorms."

Evidence supporting Changnon and Changnon's conclusion can be found in the work of Paul Kocin of The Weather Channel and Louis Uccellini of the National Weather Service (Kocin and Uccellini, 2004; Squires and Lawrimore, 2006). The authors created a scale to classify snowstorms, called the Northeast Snowfall Impact Scale (NESIS), that characterizes and ranks high-impact Northeast snowstorms. These storms typically cover large areas with snowfall accumulations of 10 inches or more. NESIS uses population information in addition to meteorological measurements to help communicate the social and economic impact of snowstorms. Storms are put into five categories with 1 being the smallest ("notable") and 5 being the largest ("extreme").

Using the NESIS scale, the National Oceanic and Atmospheric Administration's National Climatic Data Center created a list of 36 "high-impact snowstorms that affected the Northeast urban corridor," with the earliest storm occurring in 1956 and the most recent on March 1-3, 2009 (NOAA, 2009). Since population has increased in the Northeast over time, more recent storms rank higher on the NESIS scale even if they are no more severe than storms of the past. Nevertheless, fully half (6) of the highest rated (most severe) snowstorms on this record occurred before 1970, as did 14 of all 36 storms in the record. The three most severe storms occurred in 1993, 1996, and 2003, but the next three worst happened in 1960, 1961, and 1964.

Similarly, the National Weather Service tracks the "biggest snowstorms on record" for several cities, with tables showing the dates of the storms and number of inches of snowfall for each posted on its Web site (NWS, 2009). The table for Washington DC shows 15 snowstorms, with five storms having occurred since 1970, four between 1930 and 1970, and six prior to 1930. The biggest snowstorm ever to hit Washington DC arrived in January 1772, when 36 inches fell in the Washington-Baltimore area. It has been called the Washington-Jefferson snowstorm because it was recorded in both of their diaries. It is unlikely that human activity could have contributed to the severity of that storm, or to any other storm prior to the start of significant anthropogenic greenhouse gas emissions in the 1940s.

The research summarized in this section reveals that there has been no trend toward less snowfall or snow accumulation, or toward more snowstorms, in North America during the second half of the twentieth century. This record contradicts either the claim that warmer temperatures will lead to more snowfall and winter storms, or the claim that North America experienced warmer winter temperatures during the past half-century. In either case, the IPCC's claims in this regard must be erroneous.

Additional information on this topic, including reviews on snow not discussed here, can be found at http://www.co2science.org/subject/s/subject_s.php under the heading Snow.

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6.8. Storm Surges

One of the many catastrophes said to be caused by global warming is the heaving of the world's seas beyond their normal bounds in more frequent and increasingly violent storm surges. The following section summarizes the findings of a number of pertinent papers.

De Lange and Gibb (2000) analyzed trends in sea-level data obtained from several tide gauges located within Tauranga Harbor, New Zealand, over the period 1960-1998. In studying seasonal, interannual, and decadal distributions of storm surge data, they discovered a considerable decline in the annual number of storm surge events in the latter half of the nearly four-decade-long record. A similar trend was noted in the magnitude of storm surges. In addition, maximum water levels, including tides, also declined over the past two decades.

Decadal variations in the data were linked to the Inter-decadal Pacific Oscillation (IPO) and the El Niño-Southern Oscillation (ENSO), with La Niña events producing more storm surge days than El Niño events. In addition, wavelet analyses of annual storm surge frequency data indicated that before 1978 the frequency "was enhanced by the IPO, and subsequently it has been attenuated."

Pirazzoli (2000) analyzed tide-gauge and meteorological (wind and atmospheric pressure) data for the slightly longer period of 1951-1997 along the northern portion of the Atlantic coast of France. This effort revealed that the number of atmospheric depressions (storms) and strong surge winds in this region "are becoming less frequent" and that "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding." Pirazzoli suggests these findings should be "reassuring," especially for those concerned about coastal flooding.

Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, in an attempt to determine historical trends of positive and negative surge anomalies. This work led to the discovery that weak and moderate positive surges did not exhibit any definite trends, while strong positive surges clearly became less frequent over the period of study, even in the face of a gradually rising sea level, "presumably," in Raicich's words, "as a consequence of a general weakening of the atmospheric activity," which was likewise found by Pirazzoli to be the case for Brittany.

Based on data for the somewhat longer period of 1901-1990, Wroblewski (2001) determined there was a linear increase in mean annual sea level at the southern Baltic seaport of Kolobrzeg of 12 ± 2 cm per century. Over this same period, however, there was no trend in annual sea-level maxima. Two high values stood out above the rest in the 1980s, but two similar spikes occurred in the 1940s; there were half-a-dozen comparable high values in the first two decades of the record. In light of the slow upward trend in mean sea level, therefore, it is extremely surprising that annual maximum sea levels due to storm surges did not likewise rise over the past century. One can only conclude these events must have become less intense over the same time interval.

Utilizing a full century of data, Zhang *et al*. (2000) analyzed 10 very long records of storm surges derived from hourly tide gauge measurements made along the east coast of the United States, in order to calculate indexes of count, duration and integrated intensity of surge-producing storms that provide objective, quantitative, and comprehensive measures of historical storm activities in this region. The end result of their comprehensive undertaking was a demonstrable lack of "any discernible long-term secular trend in storm activity during the twentieth century," which finding, in their words, "suggests a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 years."

Looking considerably further back in time, Woodworth and Blackman (2002) analyzed four discontinuous sets of high-water data from the UK's Liverpool waterfront that span the period 1768-1999, looking for changes in annual maximum high water (tide plus surge), surge at annual maximum high water (surge component of annual maximum high water), and annual maximum surge-at-high-water. They could detect no significant trends in the first two parameters over the period of study; but they found that the annual maximum surge-at-high-water declined at a rate of 0.11 ± 0.04 meters per century. This finding suggests the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (Little Ice Age) than during the latter part (Current Warm Period).

Last, in what is the longest look back in time of the papers treating this subject, Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeastern Australia located between latitudes 13 and 24°S by (1) geologically dating and topographically surveying landform features left by surges produced by historic hurricanes and (2) running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. This work revealed that several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred over the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of study. The two researchers also report that the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The twentieth century, however, was totally devoid of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

It seems safe to conclude that storm surges around the world have not responded to rising temperatures during the twentieth century. In the majority of cases investigated, they have decreased.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/o/oceanstormsurge.php.

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6.9. Temperature Variability

One more measure of climatic change is temperature variability. Has the earth experienced more record highs or lows of temperature during the Current Warm Period?

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

Similar results were obtained by McManus *et al*. (1999), who also examined a half-million-year-old deep-sea sediment core from the eastern North Atlantic. Significant SST oscillations were again noted throughout the record, and they too were of much greater amplitude during glacial periods (4 to 6°C) than during interglacials (1 to 2°C). Likewise, in another study of a half-million-year-long sediment core from the same region, Helmke *et al*. (2002) found that the most stable of all climates held sway during what they called "peak interglaciations" or periods of greatest warmth. In this regard, we note that the temperatures of all four of the interglacials that preceded the one in which we currently live were warmer than the present one, and by an average temperature in excess of 2°C, as determined by Petit *et al*. (1999). Hence, even if the earth were to continue its recent (and possibly ongoing) recovery from the global chill of the Little Ice Age, that warming likely would lead to a state of reduced temperature variability, as evidenced by real-world data pertaining to the past half-million years.

Shifting our focus to the past millennium, Cook *et al*. (2002) report the results of a tree-ring study of long-lived silver pines on the West Coast of New Zealand's South Island. The chronology they derived provides a reliable history of Austral summer temperatures from AD 1200 to 1957, after which measured temperatures were used to extend the history to 1999. Cook *et al*. say their reconstruction indicates "there have been several periods of above and below average temperature that have not been experienced in the 20th century." This finding indicates that New Zealand temperatures grew less variable over the twentieth century.

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

In yet another part of the world, many long tree-ring series obtained from widely spaced Himalayan cedar trees were used by Yadav *et al*. (2004) to develop a temperature history of the western Himalayas for the period AD 1226-2000. "Since the 16th century," to use their words, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226-1500), reflecting unstable climate during the Little Ice Age (LIA)." With respect to this greater variability of climate during colder conditions, they note that similar results have been obtained from juniper tree-ring chronologies from central Tibet (Braeuning, 2001), and that "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." Likewise, in a study of the winter half-year temperatures of a large part of China, Ge *et al*. (2003) identified greater temperature anomalies during the 1600s than in the 1980s and 1990s.

Focusing on just the past century, Rebetez (2001) analyzed day-to-day variability in two temperature series from Switzerland over the period 1901-1999, during which time the two sites experienced temperatures increases of 1.2 and 1.5°C. Their work revealed that warmer temperatures led to a reduction in temperature variability at both locations. As they describe it, "warmer temperatures are accompanied by a general reduction of variability, both in daily temperature range and in the monthly day-to-day variability." We see that even on this much finer time scale, it is cooling, not warming, that brings an increase in temperature variability.

In a study based on daily maximum (max), minimum (min), and mean air temperatures (T) from 1,062 stations of the U.S. Historical Climatology Network, Robeson (2002) computed the slopes of the relationships defined by plots of daily air temperature standard deviation vs. daily mean air temperature for each month of the year for the period 1948-1997. This protocol revealed, in Robeson's words, that "for most of the contiguous USA, the slope of the relationship between the monthly mean and monthly standard deviation of daily Tmax and Tmin—the variance response—is either negative or near-zero," which means, he describes it, that "for most of the contiguous USA, a warming climate should produce either reduced air-temperature variability or no change in air-temperature variability." He also reports that the negative relationships are "fairly strong, with typical reductions in standard deviation ranging from 0.2 to 0.5°C for every 1°C increase in mean temperature."

In Canada, according to Shabbar and Bonsal (2003), "extreme temperature events, especially those during winter, can have many adverse environmental and economic impacts." They chose to examine trends and variability in the frequency, duration, and intensity of winter (January-March) cold and warm spells during the second half of the twentieth century. From 1950-1998, they found that western Canada experienced decreases in the frequency, duration, and intensity of winter cold spells. In the east, however, distinct increases in the frequency and duration of winter cold spells occurred. With respect to winter warm spells, significant increases in both their frequency and duration were observed across most of Canada, with the exception of the extreme northeastern part of the country, where warm spells appear to be becoming shorter and less frequent. In the mean, therefore, there appear to be close-to-compensating trends in the frequency and intensity of winter cold spells in different parts of Canada, while winter warm spells appear to be increasing somewhat. As a result, Canada appears to have experienced a slight amelioration of extreme winter weather over the past half-century.

In another study that suffers from the difficulty of having but a few short decades of data to analyze, Iskenderian and Rosen (2000) studied two mid-tropospheric temperature datasets spanning the past 40 years, calculating day-to-day variability within each month, season, and year. Averaged over the entire Northern Hemisphere, they found that mid-tropospheric temperature variability exhibited a slight upward trend since the late 1950s in one of the datasets; but, as they note, "this trend is significant in the spring season only." They also admit that "the robustness of this springtime trend is in doubt," because the trend obtained from the other dataset was negative. For the conterminous United States, however, the two datasets both showed "mostly small positive trends in most seasons." But, again, none of these trends was statistically significant. Therefore, Iskenderian and Rosen acknowledge they "cannot state with confidence that there has been a change in synoptic-scale temperature variance in the mid-troposphere over the United States since 1958."

In an attempt to determine the role that might have been played by the planet's mean temperature in influencing temperature variability over the latter half of the twentieth century, Higgins *et al.* (2002) examined the influence of two important sources of Northern Hemispheric climate variability—the El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation—on winter (Jan-Mar) daily temperature extremes over the conterminous United States from 1950 to 1999. With respect to the Arctic Oscillation, there was basically no difference in the number of extreme temperature days between its positive and negative phases. With respect to the ENSO phenomenon, however, Higgins *et al.* found that during El Niño years, the total number of extreme temperature days was found to decrease by around 10 percent, while during La Niña years they increased by around 5 percent. With respect to winter temperatures across the conterminous United States, therefore, the contention that warmer global temperatures—such as are typically experienced during El Niño years—would produce more extreme weather conditions is found to be false.

Over the same time period, Zhai and Pan (2003) derived trends in the frequencies of warm days and nights, cool days and nights, and hot days and frost days for the whole of China, based on daily surface air temperature data obtained from approximately 200 weather observation stations scattered across the country. Over the period of record, and especially throughout the 1980s and 1990s, there were increases in the numbers of warm days and nights, while there were decreases in the numbers of cool days and nights, consistent with an overall increase in mean daily temperature. At the extreme hot end of the temperature spectrum, however, the authors report that "the number of days with daily maximum temperature above 35°C showed a slightly decreasing trend for China as a whole," while at the extreme cold end of the spectrum, the number of frost days with daily minimum temperature below 0°C declined at the remarkable rate of 2.4 days per decade.

In considering this entire body of research, it is evident that air temperature variability almost always decreases when mean air temperature rises.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/e/extremetemp.php.

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6.10. Wildfires

As stated by the IPCC, "an intensification and expansion of wildfires is likely globally, as temperatures increase and dry spells become more frequent and more persistent" (IPCC, 2007-II). Below, we test this claim by reviewing the results of studies conducted in various parts of the world, ending with a recent satellite study that evaluated the globe as a whole.

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

In another Canadian study that sheds important new light on this subject, four forest scientists investigated "regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years vs. non-fire years in the Waswanipi area of northeastern Canada [49.5-50.5°N, 75-76.5°W], and the long-term relationship with large-scale climate variations ... using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps." The results of their investigation revealed that instead of the interval of time between wildfires shortening as time progressed and the climate warmed, there was "a major lengthening of the fire cycle." In addition, the four researchers note that "in the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 [or the "end of the Little Ice Age," as they describe it] (Bergeron and Archambault, 1993; Larsen, 1996) and a further decrease after 1940 (Bergeron *et al*., 2001, 2004a,b, 2006)."

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

Pitkanen *et al*. (2003) constructed a Holocene fire history of dry heath forests in eastern Finland on the basis of charcoal layer data obtained from two small mire basins and fire scars on living and dead pine trees. This work revealed a "decrease in fires during climatic warming in the Atlantic chronozone (about 9000-6000 cal. yr. BP)," prompting them to conclude that "the very low fire frequency during the Atlantic chronozone despite climatic warming with higher summer temperatures, is contrary to assumptions about possible implications of the present climatic warming due to greenhouse gases."

Thereafter, the researchers observed an increase in fire frequency at the transition between the Atlantic and Subboreal chronozones around 6,000 cal. yr. BP, noting that "the climatic change that triggered the increase in fire frequency was cooling and a shift to a more continental climate." In addition, they report that the data of Bergeron and Archambault (1993) and Carcaillet *et al*. (2001) from Canada suggest much the same thing; i.e., fewer boreal forest fires during periods of greater warmth. Consequently, "as regards the concern that fire frequency will increase in [the] near future owing to global warming," the researchers say their data "suggest that fires from 'natural' causes (lightning) are not likely to increase significantly in eastern Finland and in geographically and climatically related areas."

Back in Canada, Girardin *et al*. (2006) introduced their study of the subject by citing a number of predictions that "human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures," noting that "climate change therefore could cause longer fire seasons (Wotton and Flannigan, 1993), with greater fire activity and greater incidence of extreme fire activity years (Colombo *et al*., 1998; Parker *et al*., 2000)." To see if any of these predictions might have recently come to pass, they reconstructed a history of area burned within the province of Ontario for the period AD 1781-1982 from 25 tree-ring width chronologies obtained from various sites throughout the province. An increase in area burned within Ontario is known to have occurred from 1970 through 1981 (Podur *et al*., 2002).

The three researchers report that "while in recent decades area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s," noting further that "the most recent increase in area burned in the province of Ontario (circa 1970-1981) [Podur *et al*., 2002] was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s-1960s)."

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

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

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

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

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

With respect to their central thesis, which appears to be well supported by both the SFP and Yellowstone data, we agree with Pierce *et al*. that both the size and severity of large-event stand-replacing fires tend to increase with increasing temperature in the part of the world and for the specific forests they studied. We note that the Yellowstone data also depict a sharp drop in large-event fire frequency and severity during the earlier Dark Ages Cold Period, which followed on the heels of the preceding peak in such fires that was concomitant with the still earlier Roman Warm Period.

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

So what is the case for the world as a whole—i.e., what is the net result of the often-opposite wildfire responses to warming that are typical of different parts of the planet?

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

Although one can readily identify specific parts of the planet that have experienced both significant increases and decreases in land area burned over the last two or three decades of the twentieth century, as we have done in the materials reviewed above, for the globe as a whole there was no relationship between global warming and total area burned over this latter period, during which time it is claimed the world warmed at a rate and to a degree that were both unprecedented over the past millennium.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/f/firegw.php.

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