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4.3. Precipitation Trends

In spite of the fact that global circulation models (GCMs) have failed to accurately reproduce observed patterns and totals of precipitation (Lebel *et al*., 2000), model predictions of imminent CO_2-induced global warming often suggest that this phenomenon should lead to increases in rainfall amounts and intensities. Rawlins *et al*. (2006) state that "warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation," citing as the basis for this statement the Arctic Climate Impact Assessment (2005). Peterson *et al*. (2002) have written that "both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature," citing the works of Manabe and Stouffer (1994) and Rahmstorf and Ganopolski (1999). Similarly, Kunkel (2003) says "several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al*., 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998)."

Many scientists are examining historical precipitation records in an effort to determine how temperature changes of the past millennium have impacted these aspects of earth's hydrologic cycle. In this section, we review what some of them have learned about rainfall across the globe, starting with Africa.

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

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4.3.1. Global

Huntington (2006) notes there is "a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al*., 1991; Loaciga *et al*., 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al*., 2001)," and in reviewing the scientific literature on precipitation, he concludes that on a globally averaged basis, "precipitation over land increased by about 2% over the period 1900-1998 (Dai *et al*., 1997; Hulme *et al*., 1998)."

New *et al*. (2001) also reviewed several global precipitation datasets, analyzing the information they contain to obtain a picture of precipitation patterns over the twentieth century. In their case, they determined that precipitation over the land area of the globe was mostly below the century-long mean over the first decade-and-a-half of the record, but that it increased from 1901 to the mid-1950s, whereupon it remained above the century-long mean until the 1970s, after which it declined by about the same amount to 1992 (taking it well below the century-long mean), whereupon it recovered and edged upward towards the century mean. Hence, for the entire century, there was indeed a slight increase in global land area precipitation; but since 1915 there was essentially no net change.

For the oceanic portion of the world between 30°N and 30°S, the record of which begins in 1920, there was an overall decrease of about 0.3 percent per decade. For the world as a whole, which is 70 percent covered by water, there may well have been a slight decrease in precipitation since about 1917 or 1918.

Concentrating on the last half of the twentieth century, Neng *et al*. (2002) analyzed data from 1948 to 2000 in a quest to determine the effect of warm ENSO years on annual precipitation over the land area of the globe. In doing so, they found some regions experienced more rainfall in warm ENSO years, while others experienced *less*. However, in the words of the researchers, "in warm event years, the land area where the annual rainfall was reduced is far greater than that where the annual rainfall was increased, and the reduction is more significant than the increase." Consequently, whereas state-of-the-art climate models nearly always predict more precipitation in a warming world, the data of Neng *et al*.'s study depict just the opposite effect over the land area of the globe.

Most recently—and noting that "the Global Precipitation Climatology Project (GPCP) has produced merged satellite and in situ global precipitation estimates, with a record length now over 26 years beginning 1979 (Huffman *et al*., 1997; Adler *et al*., 2003)"—Smith *et al*. (2006) used empirical orthogonal function (EOF) analysis to study annual GPCP-derived precipitation variations over the period of record. In doing so, they found that the first three EOFs accounted for 52 percent of the observed variance in the precipitation data. Mode 1 was associated with mature ENSO conditions and correlated strongly with the Southern Oscillation Index, while Mode 2 was associated with the strong warm ENSO episodes of 1982/83 and 1997/98. Mode 3 was uncorrelated with ENSO but was associated with tropical trend-like changes that were correlated with interdecadal warming of tropical sea surface temperatures.

Globally, Smith *et al*. report that "the mode 3 variations average to near zero, so this mode does not represent any net change in the amount of precipitation over the analysis period." Consequently, over the period 1979-2004, when the IPCC claims the world warmed at a rate and to a degree that was unprecedented over the past two millennia, Smith *et al*. found that most of the precipitation variations in their global dataset were "associated with ENSO and have no trend." As for the variations that were *not* associated with ENSO and that *did* exhibit trends, they say that the trends were associated "with increased tropical precipitation over the Pacific and Indian Oceans associated with local warming of the sea." However, they note that this increased precipitation was "balanced by decreased precipitation in other regions," so that "the global average change [was] near zero."

Over the earth as a whole, therefore, it would appear from Smith *et al*.'s study, as well as from the other studies described above, that one of the major theoretical expectations of the climate modeling community remains unfulfilled, even under the supposedly highly favorable thermal conditions of the last quarter-century.

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

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4.3.2. Africa

Richard *et al*. (2001) analyzed summer (January-March) rainfall totals in southern Africa over the period 1900-1998, finding that interannual variability was higher for the periods 1900-1933 and 1970-1998, but lower for the period 1934-1969. The strongest rainfall anomalies (greater than two standard deviations) were observed at the beginning of the century. However, the authors conclude there were "no significant changes in the January-March rainfall totals," nor any evidence of "abrupt shifts during the 20th century," suggesting that rainfall trends in southern Africa do not appear to have been influenced by CO_2-induced—or any other type of—global warming.

Nicholson and Yin (2001) report there have been "two starkly contrasting climatic episodes" in the equatorial region of East Africa since the late 1700s. The first, which began sometime prior to 1800, was characterized by "drought and desiccation." Extremely low lake levels were the norm, as drought reached its extreme during the 1820s and 1830s. In the mid to latter part of the 1800s, however, the drought began to weaken and floods became "continually high," but by the turn of the century lake levels began to fall as mild drought conditions returned. The drought did not last long, however, and the latter half of the twentieth century has seen an enhanced hydrologic cycle with a return of some lake levels to the high stands of the mid to late 1800s.

Verschuren *et al*. (2000) also examined hydrologic conditions in equatorial East Africa, but over a much longer time scale, i.e., a full thousand years. They report the region was significantly drier than it is today during the Medieval Warm Period from AD 1000 to 1270, while it was relatively wet during the Little Ice Age from AD 1270 to 1850. However, this latter period was interrupted by three episodes of prolonged dryness: 1390-1420, 1560-1625, and 1760-1840. These "episodes of persistent aridity," according to the authors, were "more severe than any recorded drought of the twentieth century."

The dry episode of the late eighteenth/early nineteenth centuries recorded in Eastern Africa has also been identified in Western Africa. In analyzing the climate of the past two centuries, Nicholson (2001) reports that the most significant climatic change that has occurred "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."

The importance of these findings is best summarized by Nicholson herself, when she states that "the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of irreversible global change." Why not? Because an even longer period of similar dry conditions occurred between 1800 and 1850, when the earth was still in the clutches of the Little Ice Age, even in Africa (Lee-Thorp *et al*., 2001). There is no reason to think that the past two- to three-decade Sahelian drought is unusual or caused by the putative higher temperatures of that period.

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

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4.3.3. Arctic

Curtis *et al*. (1998) examined a number of climatic variables at two first-order Arctic weather stations (Barrow and Barter Island, Alaska) that began in 1949, finding that both the frequency and mean intensity of precipitation at these two locations decreased over the period of record. Contemporaneously, they report that temperatures in the western Arctic increased, but that "the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere." Be that as it may, the four researchers concluded that the theoretical model-based assumption that "increased temperature leads to high precipitation ... is not valid," at least for the part of the western Arctic that was the focus of their analysis.

Lamoureux (2000) analyzed varved lake sediments obtained from Nicolay Lake, Cornwall Island, Nunavut, Canada, which were compared with rainfall events recorded at a nearby weather station over the period 1948-1978 and thereby used to reconstruct a rainfall history for the surrounding region over the 487-year period from 1500 to 1987. The results were suggestive of a small, but statistically insignificant, increase in rainfall over the course of the record. However, *heavy* rainfall was most frequent during the seventeenth and nineteenth centuries, which were the *coldest* periods of the past 400 years in the Canadian High Arctic, as well as the Arctic as a whole. In addition, Lamoureux found that "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age." Here, in a part of the planet predicted to be most impacted by CO_2-induced global warming—the Canadian High Arctic—a warming of the climate is demonstrated to *reduce* weather extremes related to precipitation.

Most recently, Rawlins *et al*. (2006) calculated trends in the spatially averaged water equivalent of annual rainfall and snowfall across the six largest Eurasian drainage basins that feed major rivers that deliver water to the Arctic Ocean for the period 1936-1999. Their results indicated that annual rainfall across the total area of the six basins decreased consistently and significantly over the 64-year period. Annual snowfall, on the other hand, exhibited "a strongly significant increase," but only "until the late 1950s." Thereafter, it exhibited "a moderately significant decrease," so that "no significant change [was] determined in Eurasian-basin snowfall over the entire 64-year period." The researchers' bottom-line finding, therefore, was that annual total precipitation (including both rainfall and snowfall) *decreased* over the period of their study; they note that this finding is "consistent with the reported (Berezovskaya *et al*., 2004) decline in total precipitation."

In light of the findings reviewed above, either (1) the theoretical arguments and model predictions that suggest that "high-latitude precipitation increases in proportion to increases in mean hemispheric temperature" are not incredibly robust, or (2) late twentieth century temperatures may not have been much warmer than those of the mid-1930s and 40s, or (3) both of the above. Any or all of these choices fail to provide support for a key claim of the IPCC.

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

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4.3.4. Asia

Kripalani *et al*. (2003) note that globally averaged temperatures are projected to rise under all scenarios of future energy use, according to the IPCC, leading to "increased variability and strength of the Asian monsoon." To see if there is any sign of such a precipitation response in real-world measurements, they examined Indian monsoon rainfall using observational data for the period 1871-2001 obtained from 306 stations distributed across the country. They discovered "distinct alternate epochs of above and below normal rainfall," which epochs "tend to last for about three decades." In addition, they report "there is no clear evidence to suggest that the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming." They also report that "studies by several authors in India have shown that there is no statistically significant trend in IMR for the country as a whole." They further report that "Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances over the Bay of Bengal and the Arabian Sea using 100-year (1890-1999) data and found significant decreasing trends." As a result, Kripalani *et al*. conclude that "there seem[s] to be no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by [the] greenhouse warming scenario in model simulations." In addition, they say that "the analysis of observed data for the 131-year period (1871-2001) suggests no clear role of global warming in the variability of monsoon rainfall over India," much as Kripalani and Kulkarni (2001) had concluded two years earlier.

Kanae *et al*. (2004) note that the number and intensity of heavy precipitation events are projected to increase in a warming world, according to the IPCC. They investigate this climate-model-derived hypothesis with digitalized hourly precipitation data recorded at the Tokyo Observatory of the Japan Meteorological Agency for the period 1890-1999. They report "many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s," and that against that backdrop, "the 1990s seems to be unprecedented." However, they note that "hourly heavy precipitation around the 1940s is even stronger/more frequent than in the 1990s." In fact, their plots of maximum hourly precipitation and the number of extreme hourly precipitation events rise fairly regularly from the 1890s to peak in the 1940s, after which declines set in that bottom out in the 1970s and then reverse to rise to endpoints in the 1990s that are not yet as high as the peaks of the 1940s.

Taking a longer view of the subject, Pederson *et al*. (2001) used tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651-1995. Analyses of both standard deviations and five-year intervals of extreme wet and dry periods of this record revealed that "variations over the recent period of instrumental data are not unusual relative to the prior record." The authors do state, however, that the reconstructions "appear to show more frequent extended wet periods in more recent decades," but they say this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." In addition, they report that spectral analysis of the data revealed significant periodicities around 12 and 20-24 years, suggesting, in their words, "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Going back even further in time, Touchan *et al*. (2003) developed two reconstructions of spring (May-June) precipitation for southwestern Turkey from tree-ring width measurements, one of which extended from 1776 to 1998 and one from 1339 to 1998. These reconstructions, in their words, "show clear evidence of multi-year to decadal variations in spring precipitation," but they report that "dry periods of 1-2 years were well distributed throughout the record" and that the same was true of wet periods of one to two years' duration. With respect to more extreme events, the period that preceded the Industrial Revolution stood out. They say "all of the wettest 5-year periods occurred prior to 1756," while the longest period of reconstructed spring drought was the four-year period 1476-79, and the single driest spring was 1746. Turkey's greatest precipitation extremes, in other words, occurred prior to the Modern Warm Period, which is just the opposite of what the IPCC claims about extreme weather and its response to global warming.

Neff *et al*. (2001) looked much further back in time (from 9,600 to 6,100 years ago), using the relationship between a ^{14}C tree-ring record and a $\delta^{18}O$ proxy record of monsoon rainfall intensity as recorded in calcite $\delta^{18}O$ data obtained from a stalagmite in northern Oman. They found the correlation between the two datasets was "extremely strong," and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the $\delta^{18}O$ record and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Consequently, because variations in ^{14}C tree-ring records are generally attributed to variations in solar activity, and because of the ^{14}C record's strong correlation with the $\delta^{18}O$ record, as well as the closely corresponding results of their spectral analyses, Neff *et al*. conclude there is "solid evidence" that both signals are responding to solar forcing.

In conclusion, evidence from Asia provides no support for the claim that precipitation in a warming world becomes more variable and intense. In fact, in some cases it tends to suggest just the opposite and provides support for the proposition that precipitation responds to cyclical variations in solar activity.

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

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4.3.5. Europe

4.3.5.1. Central

Koning and Franses (2005) conducted a detailed analysis of a century of daily precipitation data acquired at the de Bilt meteorological station in the Netherlands. Using what they call "robust nonparametric techniques," they found the cumulative distribution function of annual maximum precipitation levels remained constant throughout the period 1906-2002, leading them to conclude that "precipitation levels are not getting higher." They report that similar analyses they performed for the Netherlands' five other meteorological stations "did not find qualitatively different results."

Wilson *et al*. (2005) developed two versions of a March-August precipitation chronology based on living and historical tree-ring widths obtained from the Bavarian Forest of southeast Germany for the period 1456-2001. The first version, standardized with a fixed 80-year spline function (SPL), was designed to retain decadal and higher frequency variations, while the second version used regional curve standardization (RCS) to retain lower frequency variations. Their efforts revealed significant yearly and decadal variability in the SPL chronology, but there did not appear to be any trend toward either wetter or drier conditions over the 500-year period. The RCS reconstruction, on the other hand, better captured lower frequency variation, suggesting that March-August precipitation was substantially greater than the long-term average during the periods 1730-1810 and 1870-2000 and drier than the long-term average during the periods 1500-1560, 1610-1730, and 1810-1870. Once again, however, there was little evidence of a long-term trend.

Moving still further east in Central Europe, and covering a full millennium and a half, Solomina *et al*. (2005) derived the first tree-ring reconstruction of spring (April-July) precipitation for the Crimean peninsula, located on the northern coast of the Black Sea in the Ukraine, for the period 1620-2002, after which they utilized this chronology to correctly date and correlate with an earlier precipitation reconstruction derived from a sediment core taken in 1931 from nearby Saki Lake, thus ending up with a proxy precipitation record for the region that stretched all the way back to AD 500. In describing their findings, Solomina *et al*. say no trend in precipitation was evident over the period 1896-1988 in an instrumental record obtained at a location adjacent to the tree-sampling site. Also, the reconstructed precipitation values from the tree-ring series revealed year-to-year and decadal variability, but remained "near-average with relatively few extreme values" from about the middle 1700s to the early 1800s and again since about 1920. The most notable anomaly of the 1500-year reconstruction was an "extremely wet" period that occurred between AD 1050 and 1250, which Solomina *et al*. describe as broadly coinciding with the Medieval Warm Epoch, when humidity was higher than during the instrumental era.

The results of these several analyses demonstrate that over the period of twentieth century global warming, enhanced precipitation was not observed in Central Europe.

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

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4.3.5.2. Mediterranean

Starting at the western extreme of the continent, Rodrigo *et al*. (2001) used a variety of documentary data to reconstruct seasonal rainfall in Andalusia (southern Spain) from 1501 to 1997, after which they developed a relationship between seasonal rainfall and the North Atlantic Oscillation (NAO) over the period 1851-1997, which they used to reconstruct a history of the NAO from 1501 to 1997. This work revealed that the NAO influence on climate is stronger in winter than in other seasons of the year in Andalusia, explaining 40 percent of the total variance in precipitation; Rodrigo *et al*. make a point of noting that "the recent positive temperature anomalies over western Europe and recent dry winter conditions over southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s," as opposed to an intensification of global warming.

Also working in the Andalusia region of southern Spain, Sousa and Garcia-Murillo (2003) studied proxy indicators of climatic change in Doñana Natural Park over a period of several hundred years, comparing their results with those of other such studies conducted in neighboring regions. This work revealed that the Little Ice Age (LIA) was by no means uniform in their region of study, as it included both wetter and drier periods. Nevertheless, they cite Rodrigo *et al*. (2000) as indicating that "the LIA was characterized in the southern Iberian Peninsula by increased rainfall," and they cite Grove (2001) as indicating that "climatic conditions inducing the LIA glacier advances [of Northern Europe] were also responsible for an increase in flooding frequency and sedimentation in Mediterranean Europe." Sousa and Garcia-Murillo's work complements these findings by indicating "an aridization of the climatic conditions after the last peak of the LIA (1830-1870)," which suggests that much of Europe became drier, not wetter, as the earth recovered from the global chill of the Little Ice Age.

Moving eastward into Italy, Crisci *et al*. (2002) analyzed rainfall data collected from 81 gauges spread throughout the Tuscany region for three different periods: (1) from the beginning of each record through 1994, (2) the shorter 1951-1994 period, and (3) the still-shorter 1970-1994 period. For each of these periods, trends were derived for extreme rainfall durations of 1, 3, 6, 12, and 24 hours. This work revealed that for the period 1970-1994, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; four had positive trends at all durations and none had negative trends at all durations. For the longer 1951-1994 period, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations and one had negative trends at all durations. For the still-longer complete period of record, the majority of all stations again continued to exhibit no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations and one had negative trends at all durations, revealing no impact of twentieth century global warming one way or the other.

Working in northern Italy, Tomozeiu *et al*. (2002) performed a series of statistical tests to investigate the nature and potential causes of trends in winter (Dec-Feb) mean precipitation recorded at 40 stations over the period 1960-1995. This work revealed that nearly all of the stations experienced significant *decreases* in winter precipitation over the 35-year period of study; and by subjecting the data to a Pettitt test, they detected a significant downward shift at all stations around 1985. An Empirical Orthogonal Function analysis also was performed on the precipitation data, revealing a principal component that represented a common large-scale process that was likely responsible for the phenomenon. Strong correlation between this component and the North Atlantic Oscillation (NAO) suggested, in their words, that the changes in winter precipitation around 1985 "could be due to an intensification of the positive phase of the NAO."

Working in the eastern Basilicata region of southern Italy, where they concentrated on characterizing trends in extreme rainfall events, as well as resultant flood events and landslide events, Clark and Rendell (2006) analyzed 50 years of rainfall records (1951-2000). This work indicated, in their words, that "the frequency of extreme rainfall events in this area declined by more than 50% in the 1990s compared to the 1950s." In addition, they report that "impact frequency also decreased, with landslide-event frequency changing from 1.6/year in the period 1955-1962 to 0.3/year from 1985 to 2005, while flood frequency peaked at 1.0/year in the late 1970s before declining to less than 0.2/year from 1990." They concluded that if the climate-driven changes they observed over the latter part of the twentieth century continue, "the landscape of southern Italy and the west-central Mediterranean will become increasingly stable," or as they say in their concluding paragraph, "increased land-surface stability will be the result."

Alexandrov *et al*. (2004) analyzed a number of twentieth century datasets from throughout Bulgaria, finding "a decreasing trend in annual and especially summer precipitation from the end of the 1970s" and "variations of annual precipitation in Bulgaria showed an overall decrease." In addition, they report the region stretching from the Mediterranean into European Russia and the Ukraine "has experienced decreases in precipitation by as much as 20% in some areas."

Using analyses of tree-ring 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, including Turkey, Syria, Lebanon, Cyprus and Greece, which extend back in time as much as 600 years. Over this period, they found that May-August precipitation varied on multi-annual 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 extreme wet and dry precipitation events were found to be more variable over the intervals 1520-1590, 1650-1670, and 1850-1930, indicating that as the globe experienced the supposedly unprecedented warming of the last decades of the twentieth century, May-August precipitation in the eastern Mediterranean region actually became *less* variable than it had been in the earlier part of the century.

In conclusion, these studies of precipitation characteristics of Mediterranean Europe do not find evidence of the rising or more variable precipitation predicted by global climate models.

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

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4.3.5.3. Northern

Hanna *et al*. (2004) analyzed variations in several climatic variables in Iceland, including precipitation, over the past century in an effort to determine if there is "possible evidence of recent climatic changes" in that cold island nation. For the period 1923-2002, precipitation appeared to have increased slightly, although they questioned the veracity of the trend, citing several biases that may have corrupted the data base.

Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June-August) precipitation in east central Sweden. This work revealed there had been a high degree of variability in summer precipitation on inter-annual to decadal time scales throughout the record. Over the past century of supposedly unprecedented global warming, however, precipitation was found to have exhibited *less* variability than it did during the 150 years that preceded it.

In a study covering the longest time span of all, Linderholm and Chen (2005) derived a 500-year winter (September-April) precipitation chronology from tree-ring data obtained within the northern boreal forest zone of west-central Scandinavia. They found considerable variability, with the exception of a fairly stable period of above-average precipitation between AD 1730 and 1790. Additionally, above-average winter precipitation was found to have occurred in 1520-1561, 1626-1647, 1670-1695, 1732-1851, 1872-1892, and 1959 to the present, with the highest values reported in the early to mid-1500s; below-average winter precipitation was observed during 1504-1520, 1562-1625, 1648-1669, 1696-1731, 1852-1871, and 1893-1958, with the lowest values occurring at the beginning of the record and the beginning of the seventeenth century.

These findings demonstrate that non-CO_2-forced wetter and drier conditions than those of the present have occurred repeatedly within this region throughout the past five centuries. Similar extreme conditions may therefore be expected to naturally recur in the future.

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

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4.3.6. United States

Molnar and Ramirez (2001) conducted a detailed watershed-based analysis of precipitation and streamflow trends for the period 1948-97 in the semiarid region of the Rio Puerco Basin of New Mexico. They found "at the annual timescale, a statistically significant increasing trend in precipitation in the basin was detected." This trend was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change being observed at the high-intensity end of the spectrum. In the case of streamflow, however, there was no trend at the annual timescale; but monthly totals increased in low-flow months and decreased in high-flow months. Generally speaking, these trends are all positive for plant and animal life.

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 eleven westernmost states over the period 1910-1998. This work revealed that the long-term SWE trend of this entire region was negative, but with some significant within-region differences. In the northern Rocky Mountains and Cascades of the Pacific Northwest, for example, the trend was decidedly negative, with SWE decreasing at a rate of 0.1 to 0.2 inches per year. In the intermountain region and southern Rockies, however, there was no change in SWE with time. Cowles *et al*. additionally note 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. They too found a decreasing trend in SWE at most sites in the Pacific Northwest but more ambiguity in the southern Rockies.

These findings are particularly interesting in light of the fact that nearly all climate models suggest the planet's hydrologic cycle will be enhanced in a warming world and that precipitation will increase. This prediction is especially applicable to the Pacific Northwest of the United States, where Kusnierczyk and Ettl (2002) report that climate models predict "increasingly warm and wet winters," as do Leung and Wigmosta (1999). Over the period of Cowles *et al*.'s study, however, when there was well-documented worldwide warming, precipitation that fell and accumulated as snow in the western USA did not respond as predicted. In fact, over the Pacific Northwest, it did just the opposite.

Garbrecht and Rossel (2002) used state divisional monthly precipitation data from the US National Climatic Data Center to investigate the nature of precipitation throughout the US Great Plains from January 1895 through December 1999, finding that regions in the central and southern Great Plains experienced above-average precipitation over the last two decades of the twentieth century. This 20-year span of time was the longest and most intense wet period of the entire 105 years of record, and was primarily the result of a reduction in the number of dry years and an increase in the number of wet years. The number of very wet years, in the words of the authors, "did not increase as much and even showed a decrease for many regions." The northern and northwestern Great Plains also experienced a precipitation increase at the end of this 105-year interval, but it was primarily confined to the final decade of the twentieth century; and again, as Garbrecht and Rossel 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."

Looking at the entire conterminous United States from 1895-1999, McCabe and Wolock (2002) evaluated and analyzed (1) values of annual precipitation minus annual potential evapotranspiration, (2) surplus water that eventually becomes streamflow, and (3) the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. Their work revealed that for the country as a whole, there was a statistically significant increase in the first two of these three parameters, while for the third there was no change. In describing the significance of these findings, McCabe and Wolock say "there is concern that increasing concentrations of atmospheric carbon dioxide and other radiatively active gases may cause global warming and ... adversely affect water resources." The results of their analyses, however, reveal that over the past century of global warming, just the opposite has occurred, at least within the conterminous United States: moisture has become more available, while there has been no change in the amount of water required for optimum plant growth.

Also studying the conterminous United States were Kunkel *et al*. (2003), who analyzed a new data base of daily precipitation observations for the period 1895-2000. This effort indicated "heavy precipitation frequencies were relatively high during the late 19th/early 20th centuries, decreasing to a minimum in the 1920s and '30s, followed by a general increase into the 1990s." More specifically, they note that "for 1-day duration events, frequencies during 1895-1905 are comparable in magnitude to frequencies in the 1980s and 1990s," while "for 5- and 10-day duration events, frequencies during 1895-1905 are only slightly smaller than late 20th century values."

In commenting on these findings, Kunkel *et al*. note that since enhanced greenhouse gas forcing of the climate system was very small in the early years of this record, the elevated extreme precipitation frequencies of that time "were most likely a consequence of naturally forced variability," which further suggests, in their words, "the possibility that natural variability could be an important contributor to the recent increases." This is also the conclusion of Kunkel (2003), who in a review of this and other pertinent studies states that frequencies of extreme precipitation events in the United States in the late 1800s and early 1900s "were about as high as in the 1980s/1990s." Consequently, he too concludes that "natural variability in the frequency of precipitation extremes is quite large on decadal time scales and cannot be discounted as the cause or one of the causes of the recent increases."

Working with proxy data that extend much further back in time, 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 research revealed that although region-wide precipitation during the twentieth century was higher than what was experienced during the preceding three centuries, it was also "less variable compared to other periods in the past," both of which characteristics are huge positive developments for both man and nature in this important region of California.

In a similar study, Gray *et al*. (2003) examined 15 tree ring-width series that had been used in previous reconstructions of drought for evidence of low-frequency variation in precipitation in five regional composite chronologies pertaining to the central and southern Rocky Mountains. They say "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 also note that "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase PDO [Pacific Decadal Oscillation] with the warm phase AMO [Atlantic Multidecadal Oscillation] (Cayan *et al*., 1998; Barlow *et al*., 2001; Enfield *et al*., 2001)," something they envision happening in both the severe drought of the 1950s and the late sixteenth century megadrought.

Going back even further in time, 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 from a network of 19 tree-ring chronologies. With respect to drought, they found "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570-97, 1664-70, the 1740s, the 1770s, and the late 1800s." They also note that the 1950s drought "was large in scale and severity, but it only lasted from approximately 1950 to 1956," whereas the sixteenth century megadrought lasted more than four times 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." They also note that "the most persistent and extreme wet interval occurred in the 1330s."

Regarding the causes of the different precipitation extremes, Ni *et al*. say that "the 1950s drought corresponds to La Niña/-PDO [Pacific Decadal Oscillation] and the opposite polarity [+PDO] corresponds to the post-1976 wet period," which leads them to hypothesize that "the prominent shifts seen in the 1,000-year reconstructions in Arizona and New Mexico may also be linked to strong shifts of the coupled ENSO-PDO system." For the particular part of the world covered by their study, therefore, there appears to be nothing unusual about the extremes of both wetness and dryness experienced during the twentieth century.

In another equally long study, but on the opposite side of the country, Cronin *et al*. (2000) measured and analyzed salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United Sates, in an effort to examine precipitation variability in the surrounding watershed over the past 1,000 years. They found a high degree of decadal and multidecadal variability between wet and dry conditions throughout the record, where regional precipitation totals fluctuated between 25 percent and 30 percent, often in "extremely rapid [shifts] occurring over about a decade." Precipitation over the last two centuries, however, was on average greater than what it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250-1350), when the climate was judged to have been "extremely wet." In addition, it was determined that this region, like the southwestern United States, had experienced several "mega-droughts," lasting from 60-70 years in length, some of which Cronin *et al*. describe as being "more severe than twentieth century droughts."

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

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

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4.3.7. Canada and Mexico

Kunkel (2003) reported that "several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al*., 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998)." Consequently, Kunkel looked for such a signal in precipitation data from Canada that covered much of the past century. His search, however, was in vain, as the data indicated, in his words, that "there has been no discernible trend in the frequency of the most extreme events in Canada."

Zhang *et al*. (2001) also studied the temporal characteristics of heavy precipitation events across Canada, using what they describe as "the most homogeneous long-term dataset currently available for Canadian daily precipitation." Their efforts revealed that decadal-scale variability was a dominant feature of both the frequency and intensity of the annual number of extreme precipitation events, but they found "no evidence of any significant long-term changes." When the annual data were divided into seasonal data, however, an increasing trend in the number of extreme autumn snowfall events was noted; and an investigation into precipitation totals (extreme plus non-extreme events) revealed a slightly increasing trend that was attributed to increases in the number of non-heavy precipitation events. Zhang *et al*.'s overall conclusion was 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."

Taking a longer view of the subject was Lamoureux (2000), who analyzed varved lake sediments obtained from Nicolay Lake, Cornwall Island, Nunavut, Canada, and compared the results with rainfall events recorded at a nearby weather station over the period 1948-1978, which comparison enabled the reconstruction of a rainfall history for the location over the 487-year period from 1500 to 1987. This history was suggestive of a small, but statistically insignificant, increase in total rainfall over the course of the record. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, which were the coldest periods of the past 400 years in the Canadian High Arctic, as well as the Arctic as a whole. In addition, Lamoureux says that "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age."

This study, like the others discussed above, contradicts the IPCC's claim that extreme precipitation events become more frequent and more severe with increasing temperature. Here in the Canadian High Arctic, in a part of the planet predicted to be most impacted by CO_2-induced global warming, rising temperatures have been shown to *reduce* precipitation extremes, even in the face of a slight increase in total precipitation.

South of the United States, Diaz *et al*. (2002) created a 346-year history of winter-spring (November-April) precipitation for the Mexican state of Chihuahua, 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. This exercise revealed, in their words, 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 fact makes it sound like the twentieth century was highly anomalous in this regard, it was not. Two of those three worst drought years occurred during a decadal period of average to slightly above-average precipitation, so the three years were not representative of long-term droughty conditions.

Diaz *et al*. additionally report that "the longest drought indicated by the smoothed reconstruction lasted 17 years (1948-1964)," which again makes the twentieth century look unusual in this regard. However, for several of the years of that interval, precipitation values were only slightly below normal; and 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 a long period of high winter-spring precipitation that stretched from 1905 to 1932; and following the major drought of the 1950s, precipitation remained at, or just slightly above, normal for the remainder of the record. Finally, with respect to the entire 346 years, there was no long-term trend in the data, nor was there any evidence of a significant departure from that trend over the course of the twentieth century. Consequently, Chihuahua's precipitation history did not differ in any substantial way during the twentieth century from what it was over the prior quarter of a millennium, suggesting that neither twenteith century anthropogenic CO_2 emissions nor 20th-century warming—whether natural or human-induced—significantly impacted precipitation in that part of 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/p/precipnortham.php.

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4.4. Streamflow

Model projections suggest that CO_2-induced global warming will adversely impact earth's water resources by inducing large changes in global streamflow characteristics. As a result, many scientists are examining proxy streamflow records in an effort to determine how temperature changes of the twentieth century may or may not have impacted this aspect of the planet's hydrologic cycle. This is related to forecasts of droughts, floods, and precipitation variability, issues that are addressed in greater detail in Chapter 6.

A recent global study of this issue is Milliman *et al*. (2008), who computed temporal discharge trends for 137 rivers over the last half of the twentieth century that provide what they call a "reasonable