4

Observations: Glaciers, Sea Ice, Precipitation, and Sea Level

Introduction

The Intergovernmental Panel on Climate Change (IPCC) alleges that "recent decreases in ice mass are correlated with rising surface air temperatures," and more specifically that "the late 20th-century glacier wastage likely has been a response to post-1970 warming. Strongest mass losses per unit area have been observed in Patagonia, Alaska and northwest USA and southwest Canada. Because of the corresponding large areas, the largest contributions to sea level rise came from Alaska, the Arctic and the Asian high mountains. Taken together, the ice sheets in Greenland and Antarctica have *very likely* been contributing to sea level rise over 1993 to 2003 [italics in the original]" (IPCC, 2007-I, p. 339).

It should be obvious, but apparently is not, that such facts as melting glaciers and disappearing Arctic sea ice, while interesting, are entirely irrelevant to illuminating the causes of warming. Any significant warming, whether anthropogenic or natural, will melt ice—often quite slowly. Therefore, claims that anthropogenic global warming (AGW) is occurring that are backed by such accounts are simply confusing the consequences of warming with the causes—a common logical error. In addition, fluctuations of glacier mass, sea ice, precipitation, and sea level depend on many factors other than temperature and are poor measuring devices for global warming.

This chapter summarizes the extensive scientific literature on glaciers, sea ice, precipitation, and sea level rise that frequently contradicts and rarely reinforces the IPCC's claims quoted above. Glaciers around the world are continuously advancing and retreating, with no evidence of a trend that can be linked to CO_2 concentrations in the air. The same is largely true of sea ice, precipitation patterns, and sea levels: all fluctuate in response to processes that are unrelated to CO_2, and therefore cannot be taken either as signs of anthropogenic global warming or of climate disasters that may be yet to come.

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4.1. Glaciers

Model studies indicate that CO_2-induced global warming will result in significant melting of earth's glaciers, contributing to a rise in global sea level. In this section, we examine global trends and data from

Africa, Antarctica, the Arctic, Europe, North America, and South America. Additional information on this topic, including reviews of glaciers not discussed here, can be found at http://www.co2science.org/subject/g/subject_g.php under the heading Glaciers.

4.1.1. Global

The full story must begin with a recognition of just how few glacier data exist. Of the 160,000 glaciers presently known to exist, only 67,000 (42 percent) have been inventoried to any degree (Kieffer *et al*., 2000). Mass balance data (which would be positive for growth, negative for shrinkage) exist for more than a single year for only slightly more than 200 (Braithwaite and Zhang, 2000). When the length of record increases to *five* years, this number drops to 115; and if both winter and summer mass balances are required, the number drops to 79. Furthermore, if *10* years of record is used as a cutoff, only 42 glaciers qualify. This lack of glacial data, in the words of Braithwaite and Zhang, highlights "one of the most important problems for mass-balance glaciology" and demonstrates the "sad fact that many glacierized regions of the world remain unsampled, or only poorly sampled," suggesting we really know very little about the true state of most of the world's glaciers.

During the fifteenth through nineteenth centuries, widespread and major glacier advances occurred during a period of colder global temperature known as the Little Ice Age (Broecker, 2001; Grove, 2001). Many records indicate widespread glacial retreat as temperatures began to rise in the mid- to late-1800s and many glaciers returned to positions characteristic of pre-Little Ice Age times. In many instances the *rate* of glacier retreat has not increased over the past 70 years, during a time when the atmosphere experienced the bulk of the increase in its CO_2 content.

In an analysis of Arctic glacier mass balance, Dowdeswell *et al*. (1997) found that of the 18 glaciers with the longest mass balance histories, just over 80 percent displayed negative mass balances over their periods of record. Yet they additionally report that "almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance." Although these Arctic glaciers continue to lose mass, as they have probably done since the end of the Little Ice Age, they are losing smaller amounts each year, which is hardly what one would expect in the face of what some incorrectly call the "unprecedented" warming of the latter part of the twentieth century.

Similar results have been reported by Braithwaite (2002), who reviewed and analyzed mass balance measurements of 246 glaciers from around the world that were made between 1946 and 1995. According to Braithwaite, "there are several regions with highly negative mass balances in agreement with a public perception of 'the glaciers are melting,' but there are also regions with positive balances." Within Europe, for example, he notes that "Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980-95." And when results for the whole world are combined for this most recent period of time, Braithwaite notes that "there is no obvious common or global trend of increasing glacier melt in recent years."

As for the glacier with the longest mass balance record of all, the Storglaciaren in northern Sweden, for the first 15 years of its 50-year record it exhibited a negative mass balance of little trend. Thereafter, however, its mass balance began to trend upward, actually becoming positive over about the last decade (Braithwaite and Zhang, 2000).

Global data on glaciers do not support claims made by the IPCC that most claciers are retreating or melting. Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/g/glaciers.php.

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4.1.2. Africa

On the floor of the U.S. Senate in 2004, Arizona Senator John McCain described his affection for the writings of Ernest Hemingway, especially his famous short story, "The Snows of Kilimanjaro." Then, showing photos of the magnificent landmark taken in 1993 and 2000, he attributed the decline of glacial ice atop the mount during the intervening years to CO_2-induced global warming, calling this attribution a fact "that cannot be refuted by any scientist."

New York Senator Hillary Clinton echoed Senator McCain's sentiments. Displaying a second set of photos taken from the same vantage point in 1970 and 1999—the first depicting "a 20-foot-high glacier" and the second "only a trace of ice"—she said that in those pictures "we have evidence in the most dramatic way possible of the effects of 29 years of global warming." In spite of the absolute certitude with which the two senators expressed their views on the subject, which allowed for no "wiggle room" whatsoever, both of them were wrong.

Modern glacier recession on Kilimanjaro began around 1880, approximately the same time the planet began to recover from the several-hundred-year cold spell of the Little Ice Age. As a result, a number of people, including the aforementioned senators, declared that the ice fields retreated *because* of the rising temperatures, encouraged in this contention by a few reports in the scientific literature (Alverson *et al.*, 2001; Irion, 2001; Thompson *et al.*, 2002). This view of the subject, however, is "highly simplified," in the words of a trio of glaciologists (Molg *et al.*, 2003b), who noted that "glacierization in East Africa is limited to three massifs close to the equator: Kilimanjaro (Tanzania, Kenya), Mount Kenya (Kenya), and Rwenzori (Zaire, Uganda)." All three sites experienced strong ice field recession over the past century or more. In that part of the world, however, they report "there is no evidence of a sudden change in temperature at the end of the 19th century (Hastenrath, 2001)," and that "East African long-term temperature records of the twentieth century show diverse trends and do not exhibit a uniform warming signal (King'uyu *et al.*, 2000; Hay *et al.*, 2002)." With respect to Kilimanjaro, they say "since February 2000 an automatic weather station has operated on a horizontal glacier surface at the summit's Northern Icefield," and "monthly mean air temperatures only vary slightly around the annual mean of -7.1°C, and air temperatures [measured by ventilated sensors, e.g., Georges and Kaser (2002)] never rise above the freezing point," which makes it pretty difficult to understand how ice could *melt* under such conditions.

So what caused the ice fields of Kilimanjaro to recede so steadily for so many years? Citing "historical accounts of lake levels (Hastenrath, 1984; Nicholson and Yin, 2001), wind and current observations in the Indian Ocean and their relationship to East African rainfall (Hastenrath, 2001), water balance models of lakes (Nicholson and Yin, 2001), and paleolimnological data (Verschuren *et al.*, 2000)," Molg *et al.* say "all data indicate that modern East African climate experienced an abrupt and marked drop in air humidity around 1880," and they add that the resultant "strong reduction in precipitation at the end of the 19th century is the main reason for modern glacier recession in East Africa," as it considerably reduces glacier mass balance accumulation, as has been demonstrated for the region by Kruss (1983) and Hastenrath (1984). In addition, they note that "increased incoming shortwave radiation due to decreases in cloudiness—both effects of the drier climatic conditions—plays a decisive role for glacier retreat by increasing ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Molg *et al.*, 2003a)."

In further investigating this phenomenon, Molg *et al.* applied a radiation model to an idealized representation of the 1880 ice cap of Kilimanjaro, calculating the spatial extent and geometry of the ice cap for a number of subsequent points in time and finding that "the basic evolution in spatial distribution of ice bodies on the summit is modeled well." The model they used, which specifically addresses the unique configuration of the summit's vertical ice walls, provided "a clear indication that solar radiation is the main climatic parameter governing and maintaining ice retreat on the mountain's summit plateau in the drier climate since ca. 1880." Consequently, Molg *et al.* concluded that "modern glacier retreat on Kilimanjaro is much more complex than simply attributable to 'global warming only'." Indeed, they say it is "a process driven by a complex combination of changes in several different climatic parameters [e.g., Kruss, 1983; Kruss and Hastenrath, 1987; Hastenrath and Kruss, 1992; Kaser and Georges, 1997; Wagnon *et al*., 2001; Kaser and Osmaston, 2002; Francou *et al*., 2003; Molg *et al*., 2003b], with humidity-related variables dominating this combination."

Kaser *et al.* (2004) similarly concluded that "changes in air humidity and atmospheric moisture content (e.g. Soden and Schroeder, 2000) seem to play an underestimated key role in tropical high-mountain climate (Broecker, 1997)." Noting that all glaciers in equatorial East Africa exhibited strong recession trends over the past century, they report that "the dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser and Noggler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Molg *et al*., 2003b)," both of which phenomena they relate to a dramatic drying of the regional atmosphere that occurred around 1880 and the ensuing dry climate that subsequently prevailed throughout the twentieth century. Kaser *et al.* conclude that all relevant "observations and facts" clearly indicate that "climatological processes other than air temperature control the ice recession in a direct manner" on Kilimanjaro, and that "positive air temperatures have not contributed to the recession process on the summit," directly contradicting Irion (2002) and Thompson *et al.* (2002), who, in their words, see the recession of Kilimanjaro's glaciers as "a direct consequence solely of increased air temperature."

In a subsequent study of the ice fields of Kilimanjaro, Molg and Hardy (2004) derived an energy balance for the horizontal surface of the glacier that comprises the northern ice field of Kibo—the only one of the East African massif's three peaks that is presently glaciated—based on data obtained from an automated weather station. This work revealed, in their words, that "the main energy exchange at the glacier-atmosphere interface results from the terms accounting for net radiation, governed by the variation in net shortwave radiation," which is controlled by surface albedo and, thus, precipitation variability, which determines the reflective characteristics of the glacier's surface. Much less significant, according to the two researchers, is the temperature-driven turbulent exchange of sensible heat, which they say "remains considerably smaller and of little importance."

Molg and Hardy conclude that "modern glacier retreat on Kilimanjaro and in East Africa in general [was] initiated by a drastic reduction in precipitation at the end of the nineteenth century (Hastenrath, 1984, 2001; Kaser *et al*., 2004)," and that reduced accumulation and increased ablation have "maintained the retreat until the present (Molg *et al*., 2003b)." Buttressing their findings is the fact, as they report it, that "detailed analyses of glacier retreat in the global tropics uniformly reveal that changes in climate variables related to air humidity prevail in controlling the modern retreat [e.g., Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al.* (2003) for the Bolivian Cordillera Real (both South American Andes); Kruss (1983), Kruss and Hastenrath (1987), and Hastenrath (1995) for Mount Kenya (East Africa); and Molg *et al.* (2003a) for the Rwenzori massif (East Africa)]." The take-home message of their study is essentially the same as that of Kaser *et al.* (2004): "Positive air temperatures have not contributed to the recession process on the summit."

Two years later, Cullen *et al*. (2006) report that "all ice bodies on Kilimanjaro have retreated drastically between 1912-2003," but they add that the highest glacial recession rates on Kilimanjaro "occurred in the first part of the twentieth century, with the most recent retreat rates (1989-2003) smaller than in any other interval." In addition, they say no temperature trends over the period 1948-2005 have been observed at the approximate height of the Kilimanjaro glaciers, but that there has been a small decrease in the region's specific humidity over this period.

In terms of why glacier retreat on Kilimanjaro was so dramatic over the twentieth century, the six researchers note that for the mountain's plateau glaciers, there is no alternative for them "other than to continuously retreat once their vertical margins are exposed to solar radiation," which appears to have happened sometime in the latter part of the nineteenth century. They also say, in this regard, that the "vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in twentieth century climate have not altered their continuous demise." Consequently, the twentieth century retreat of Kilimanjaro's plateau glaciers is a long-term response to what we could call "relict climate change" that likely occurred in the late nineteenth century.

In the case of the mountain's slope glaciers, Cullen *et al*. say that their rapid recession in the first part of the twentieth century shows they "were drastically out of equilibrium," which they take as evidence that the glaciers "were responding to a large prior shift in climate." In addition, they report that "no footprint of multidecadal changes in areal extent of slope glaciers to fluctuations in twentieth century climate is observed, but their ongoing demise does suggest they are still out of equilibrium," and in this regard they add that their continuing but decelerating demise could be helped along by the continuous slow decline in the air's specific humidity. Consequently, and in light of all the facts they present and the analyses they and others have conducted over many years, Cullen *et al*. confidently conclude that the glaciers of Kilimanjaro "are merely remnants of a past climate rather than sensitive indicators of 20th century climate change."

Two more recent studies, Mote and Kaser (2007) and Duane *et al*. (2008) additionally reject the temperature-induced decline hypothesis for Kilimanjaro, with Duane *et al*. concluding that "the reasons for the rapid decline in Kilimanjaro's glaciers are not primarily due to increased air temperatures, but a lack of precipitation," and Mote and Kaser reporting that "warming fails spectacularly to explain the behavior of the glaciers and plateau ice on Africa's Kilimanjaro massif ... and to a lesser extent other tropical glaciers."

Clearly, the misguided rushes to judgment that have elevated Kilimanjaro's predicted demise by CO_2-induced global warming to iconic status should give everyone pause to more carefully evaluate the evidence, or lack thereof, for many similar claims related to the ongoing rise in the air's CO_2 content.

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

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4.1.3. Antarctica

In early November 2001, a large iceberg separated from West Antarctica's Pine Island Glacier. This event was of great interest to scientists because the Pine Island Glacier is currently the fastest-moving glacier in Antarctica and the continent's largest discharger of ice. Some speculate this event could herald the "beginning of the end" of the West Antarctic Ice Sheet. Scientific studies, however, suggest otherwise.

Rignot (1998) employed satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996 to determine whether it was advancing or retreating. The data indicated a retreat rate of 1.2 ± 0.3 kilometers per year over the four-year period of the study. Because the study period was so short, Rignot says the questions the study raises concerning the long-term stability of the West Antarctic Ice Sheet "cannot be answered at present."

In a subsequent study, Stenoien and Bentley (2000) mapped the catchment region of Pine Island Glacier using radar altimetry and synthetic aperture radar interferometry, after which they used the data to develop a velocity map that revealed a system of tributaries that channel ice from the catchment area into the fast-flowing glacier. By combining these velocity data with information on ice thickness and snow accumulation rates, they were able to calculate an approximate mass balance for the glacier within an uncertainty of approximately 30 percent. Their results suggested the mass balance of the catchment region was not significantly different from zero.

Shepherd *et al*. (2001) used satellite altimetry and interferometry to determine the rate of change of thickness of Pine Island Glacier's entire drainage basin between 1992 and 1999, determining that the grounded glacier thinned by up to 1.6 meters per year over this period. They note "the thinning cannot be explained by short-term variability in accumulation and must result from glacier dynamics." And since glacier dynamics are typically driven by phenomena operating on time scales of hundreds to thousands of years, this observation would argue against twentieth century warming being the cause of the thinning. Shepherd *et al.* also say they could "detect no change in the rate of ice thinning across the glacier over [the] 7-year period," which also suggests that a long-term phenomenon of considerable inertia must be at work.

What if the rate of glacier thinning—1.6 meters per year—continues unabated? Shepherd *et al.* state that "if the trunk continues to lose mass at the present rate it will be entirely afloat within 600 years." And if that happens? They say they "estimate the net contribution to eustatic sea level to be 6 mm." This means that for each century of the foreseeable future, we could expect global mean sea level to rise by one millimeter … about the thickness of a common paper clip.

Turning to other glaciers, Hall and Denton (2002) mapped the distribution and elevation of surficial deposits along the southern Scott Coast of Antarctica in the vicinity of the Wilson Piedmont Glacier, which runs parallel to the coast of the western Ross Sea from McMurdo Sound north to Granite Harbor. The chronology of the raised beaches was determined from more than 60 ^{14}C dates of organic materials they had previously collected from hand-dug excavations (Hall and Denton, 1999). They also evaluated more recent changes in snow and ice cover based on aerial photography and observations carried out since the late 1950s.

Near the end of the Medieval Warm Period—"as late as 890 ^{14}C yr BP," as Hall and Denton put it—"the Wilson Piedmont Glacier was still less extensive than it is now." They rightly conclude that the glacier had to have advanced in the past several hundred years, although they note its eastern margin has retreated in the past 50 years. They report a number of similar observations by other investigators. Citing evidence collected by Baroni and Orombelli (1994a), they note there was "an advance of at least one kilometer of the Hell's Gate Ice Shelf ... within the past few hundred years." And they report that Baroni and Orombelli (1994b) "documented post-fourteenth century advance of a glacier near Edmonson's Point." Summarizing these and other findings, they conclude that evidence from the Ross Sea area suggests "late-Holocene climatic deterioration and glacial advance (within the past few hundred years) and twentieth century retreat."

In speaking of the significance of the "recent advance of the Wilson Piedmont Glacier," Hall and Denton report that it "overlaps in time with the readvance phase known in the Alps [of Europe] as the 'Little Ice Age'," which they further note "has been documented in glacial records as far afield as the Southern Alps of New Zealand (Wardle, 1973; Black, 2001), the temperate land mass closest to the Ross Sea region." They further note that "Kreutz *et al.* (1997) interpreted the Siple Dome [Antarctica] glaciochemical record as indicating enhanced atmospheric circulation intensity at AD ~1400, similar to that in Greenland during the 'Little Ice Age' (O'Brien *et al.*, 1995)." In addition, they report that "farther north, glaciers in the South Shetland Islands adjacent to the Antarctic Peninsula underwent a late-Holocene advance, which has been correlated with the 'Little Ice Age' (Birkenmajer, 1981; Clapperton and Sugden, 1988; Martinez de Pison *et al.*, 1996; Björck *et al.*, 1996)."

In summarizing the results of their work, Hall and Denton say "the Wilson Piedmont Glacier appears to have undergone advance at approximately the same time as the main phase of the 'Little Ice Age', followed by twentieth-century retreat at some localities along the Scott Coast." This result and the others they cite make it clear that glacial activity on Antarctica has followed the pattern of millennial-scale variability that is evident elsewhere in the world: recession to positions during the Medieval Warm Period that have not yet been reached in our day, followed by significant advances during the intervening Little Ice Age.

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

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4.1.4. Arctic

Computer simulations of global climate change have long indicated the world's polar regions should show the first and severest signs of CO_2-induced global warming. If the models are correct, these signs should be especially evident in the second half of the twentieth century, when approximately two-thirds of the modern-era rise in atmospheric CO_2 occurred and earth's temperature supposedly rose to a level unprecedented in the past millennium. In this subsection, we examine historic trends in Arctic glacier behavior to determine the credibility of current climate models with respect to their polar predictions.

In a review of "the most current and comprehensive research of Holocene glaciation," along the northernmost Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, Calkin *et al.* (2001) report there were several periods of glacial advance and retreat over the past 7,000 years. Over the most recent of those seven millennia, there was a general retreat during the Medieval Warm Period that lasted for "at least a few centuries prior to A.D. 1200." Then came three major intervals of Little Ice Age glacial advance: the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century. During these very cold periods, glacier equilibrium-line altitudes were depressed from 150 to 200 m below present values, as Alaskan glaciers "reached their Holocene maximum extensions."

The mass balance records of the 18 Arctic glaciers with the longest observational histories subsequent to this time, as the planet emerged from the depths of the Little Ice Age, were studied by Dowdeswell *et al.* (1997). Their analysis showed that more than 80 percent of the glaciers displayed negative mass balances over the periods of their observation, as would be expected for glaciers emerging from the coldest part of the past millennium. Nevertheless, the scientists report that "ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age," when the magnitude of anthropogenic CO_2 emissions was much less than it has been from 1950 onward.

These observations suggest that Arctic glaciers are not experiencing any adverse effects of anthropogenic CO_2 emissions. In fact, Dowdeswell *et al.* say "there is no compelling indication of increasingly negative balance conditions which might, *a priori*, be expected from anthropogenically induced global warming." Quite to the contrary, they report that "almost 80 percent of the mass balance time series also have a positive trend, toward a less negative mass balance." Hence, although most Arctic glaciers continue to lose mass, as they have probably done since the end of the Little Ice Age, they are losing smaller amounts each year.

Additional evidence that the Arctic's glaciers are not responding to human-induced warming comes from the studies of Zeeberg and Forman (2001) and Mackintosh *et al*. (2002), who indicate there has been an *expansion* of glaciers in the European Arctic over the past few decades.

Zeeberg and Forman analyzed twentieth century changes in glacier terminus positions on north Novaya Zemlya—a Russian island located between the Barents and Kara Seas in the Arctic Ocean—providing a quantitative assessment of the effects of temperature and precipitation on glacial mass balance. Their study showed a significant and accelerated post-Little Ice Age glacial retreat in the first and second decades of the twentieth century. By 1952, the region's glaciers had experienced between 75 percent to 100 percent of their net twentieth century retreat; and during the next 50 years, the recession of more than half of the glaciers stopped, while many tidewater glaciers actually began to advance.

These glacial stabilizations and advances were attributed by the authors to observed increases in precipitation and/or decreases in temperature. For the four decades since 1961, weather stations on Novaya Zemlya, for example, show summer temperatures were 0.3 to 0.5°C colder than they were over the prior 40 years, while winter temperatures were 2.3 to 2.8°C colder than they were over that earlier period. These observations, the authors say, are "counter to warming of the Eurasian Arctic predicted for the twenty-first century by climate models, particularly for the winter season."

Other glacier observations that run counter to climate model predictions are discussed by Mackintosh *et al*. (2002), who concentrated on the 300-year history of the Solheimajokull outlet glacier on the southern coast of Iceland. In 1705, this glacier had a length of about 14.8 km; by 1740 it had grown to 15.2 km in length. Thereafter, it began to retreat, reaching a minimum length of 13.2 km in 1783. Rebounding rapidly, however, the glacier returned to its 1705 position by 1794; by 1820 it equaled its 1740 length. This maximum length was maintained for the next half-century, after which the glacier began a slow retreat that continued to about 1932, when its length was approximately 14.75 km. Then it wasted away more rapidly, reaching a second minimum-length value of approximately 13.8 km about 1970, whereupon it began to rapidly expand, growing to 14.3 km by 1995.

The current position of the outlet glacier terminus is by no means unusual. In fact, it is about midway between its maximum and minimum positions of the past three centuries. It is also interesting to note that the glacier has been growing in length since about 1970. Mackintosh *et al*. report that "the recent advance (1970-1995) resulted from a combination of cooling and enhancement of precipitation."

In another study of the Arctic, Humlum *et al*. (2005) evaluated climate dynamics and their respective impacts on high-latitude glaciers for the Archipelago of Svalbard, focusing on Spitsbergen (the Archipelago's main island) and the Longyearbreen glacier located in its relatively dry central region at 78°13'N latitude. In reviewing what was already known about the region, Humlum *et al*. report that "a marked warming around 1920 changed the mean annual air temperature (MAAT) at sea level within only 5 years from about -9.5°C to -4.0°C," which change, in their words, "represents the most pronounced increase in MAAT documented anywhere in the world during the instrumental period." Then, they report that "from 1957 to 1968, MAAT dropped about 4°C, followed by a more gradual increase towards the end of the twentieth century."

With respect to the Longyearbreen glacier, their work reveals it "has increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years," and they say that "the meteorological setting of non-surging Longyearbreen suggest this example of late-Holocene glacier growth represents a widespread phenomenon in Svalbard and in adjoining Arctic regions," which they describe as a "development towards cooler conditions in the Arctic" that "may explain why the Little Ice Age glacier advance in Svalbard usually represents the Holocene maximum glacier extension."

Climate change in Svalbard over the twentieth century was a rollercoaster ride, with temperatures rising more rapidly in the early 1920s than has been documented anywhere else before or since, only to be followed by a nearly equivalent temperature drop four decades later, both of which climatic transitions were totally out of line with what climate models suggest should have occurred. The current location of the terminus of the Longyearbreen glacier suggests that, even now, Svalbard and "adjoining Arctic regions" are experiencing some of the lowest temperatures of the entire Holocene or current interglacial, at a time when atmospheric CO_2 concentrations are higher than they have likely been for millions of years. Both of these observations are at odds with what the IPCC claims about the strong warming power of atmospheric CO_2 enrichment.

Bradwell *et al*. (2006) examined the link between late Holocene fluctuations of Lambatungnajokull (an outlet glacier of the Vatnajokull ice cap of southeast Iceland) and variations in climate, using geomorphological evidence to reconstruct patterns of glacier fluctuations and using lichenometry and tephrostratigraphy to date glacial landforms created by the glacier over the past four centuries. Results indicated that "there is a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat," and that "between 1930 and 1950 this relationship is striking." They also report that "ice-front recession was greatest during the 1930s and 1940s, when retreat averaged 20 m per year." Thereafter, they say the retreat "slowed in the 1960s," and they report "there has been little overall retreat since the 1980s."

The researchers also report that "the 20th-century record of reconstructed glacier-front fluctuations at Lambatungnajokull compares well with those of other similar-sized, non-surging, outlets of southern Vatnajokull," including Skaftafellsjokull, Fjallsjokull, Skalafellsjokull, and Flaajokull. In fact, they find "the pattern of glacier fluctuations of Lambatungnajokull over the past 200 years reflects the climatic changes that have occurred in southeast Iceland and the wider region."

Bradwell *et al*.'s findings suggest that twentieth century summer air temperature in southeast Iceland and the wider region peaked in the 1930s and 1940s, and was followed by a cooling that persisted through the end of the century. This thermal behavior is about as different as one could imagine from the claim that the warming of the globe over the last two decades of the twentieth century was unprecedented over the past two millennia. Especially is this so for a high-northern-latitude region, where the IPCC claims CO_2-induced global warming should be earliest and most strongly expressed.

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

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4.1.5. Europe

Joerin *et al*. (2006) examined glacier recessions in the Swiss Alps over the past ten thousand years based on radiocarbon-derived ages of materials found in proglacial fluvial sediments of subglacial origin, focusing on subfossil remains of wood and peat. Combining their results with earlier data of a similar nature, they then constructed a master chronology of Swiss glacier fluctuations over the course of the Holocene.

Joerin *et al*. first report discovering that "alpine glacier recessions occurred at least 12 times during the Holocene," once again demonstrating that millennial-scale oscillation of climate has reverberated throughout glacial and interglacial periods as far back in time as scientists have searched for the phenomenon. Second, they determined that glacier recessions have been decreasing in frequency since approximately 7,000 years ago, and especially since 3,200 years ago, "culminating in the maximum glacier extent of the 'Little Ice Age'." Third, the last of the major glacier recessions in the Swiss Alps occurred between about 1,400 and 1,200 years ago, according to Joerin *et al*.'s data, but between 1200 and 800 years ago, according to the data of Holzhauser *et al*. (2005) for the Great Aletsch Glacier. Of this discrepancy, Joerin *et al*. say that given the uncertainty of the radiocarbon dates, the two records need not be considered inconsistent with each other. What is more, their presentation of the Great Aletsch Glacier data indicates the glacier's length at about AD 1000—when there was fully 100 ppm *less* CO_2 in the air than there is today—was just slightly less than its length in 2002.

Also in the Swiss Alps, Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in an effort to compute the yearly mass balances of four glaciers. The results of their computations can be seen in Figure 4.1.5.1.

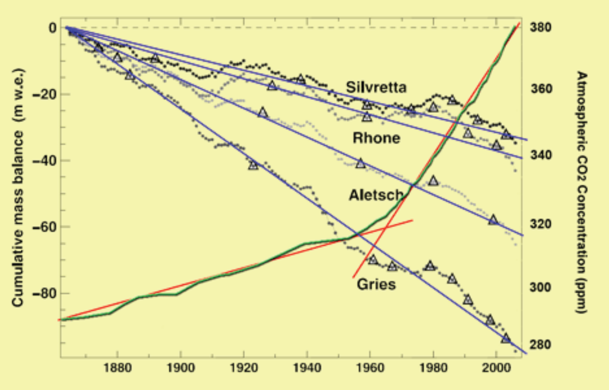

Figure 4.1.5.1. Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in the Swiss Alps to compute the yearly mass balances of four glaciers.

The most obvious conclusion to be drawn from these data is the fact that each of the four glaciers has decreased in size. But more important is the fact that the rate of shrinkage has not accelerated over time, as evidenced by the long-term trend lines we have fit to the data. There is no compelling evidence that this 14-decade-long glacial decline has had anything to do with the air's CO_2 content.

Consider, for example, the changes in atmospheric CO_2 concentration experienced over the same time period, also shown in the figure. If we compute the mean rate-of-rise of the air's CO_2 content from the start of the record to about 1950, and from about 1970 to 2006, we see that between 1950 and 1970 the rate-of-rise of the atmosphere's CO_2 concentration increased by more than five-fold, yet there were no related increases in the long-term mass balance trends of the four glaciers. It is clear that the ice loss history of the glaciers was not unduly influenced by the increase in the rate-of-rise of the air's CO_2 content that occurred between 1950 and 1970, and that their rate of shrinkage was also not materially altered by what the IPCC calls the unprecedented warming of the past few decades.

Moving to northern Europe, Linderholm et al. (2007) examined "the world's longest ongoing continuous mass-balance record" of "Storglaciaren in northernmost Sweden," which they report "is generally well correlated to glaciers included in the regional mass balance program (Holmlund and Jansson, 1999), suggesting that it represents northern Swedish glaciers." The results of their work are depicted in Figure 4.1.5.2, where we have also plotted the contemporaneous history of the atmosphere's CO_2 concentration.

In viewing the figure, it should be evident that the historical increase in the air's CO_2 content has had absolutely no discernable impact on the net mass balance history of Sweden's Storglaciaren over the past two-and-a-quarter centuries. Whereas the mean rate-of-rise of the air's CO_2 concentration over the last half-century of Storglaciaren mass balance data is fully 15 times greater than what it was over the first half-century of mass balance data (and some 40 times greater if the first and last quarter-centuries are considered), there has been no sign of any change in the long-term trend of Storglaciaren's net mass balance.

D'Orefice *et al.* (2000) assembled and analyzed a wealth of historical data to derive a history of post-Little Ice Age (LIA) shrinkage of the surface area of the southernmost glacier of Europe, Ghiacciaio del Calderone. From the first available information on the glacier's surface area in 1794, there was a very slow ice wastage that lasted until 1884, whereupon the glacier began to experience a more rapid area reduction that continued, with some irregularities, to 1990, resulting in a loss of just over half the glacier's LIA surface area.

Not all European glaciers, however, have experienced continuous declines since the end of the Little Ice Age. Hormes *et al.* (2001) report that glaciers in the Central Swiss Alps experienced two periods of readvancement, one around 1920 and another as recent as 1980. In addition, Braithwaite (2002) reports that for the period 1980-1995, "Scandinavian glaciers [have been] growing, and glaciers in the Caucasus are close to equilibrium," while "there is no obvious common or global trend of increasing glacier melt."

Fifty years of mass balance data from the storied Storglaciaren of northwestern Sweden also demonstrate a trend reversal in the late twentieth century. According to Braithwaite and Zhang (2000), there has been a significant upward trend in the mass balance of this glacier over the past 30-40 years, and it has been in a state of mass accumulation for at least the past decade.

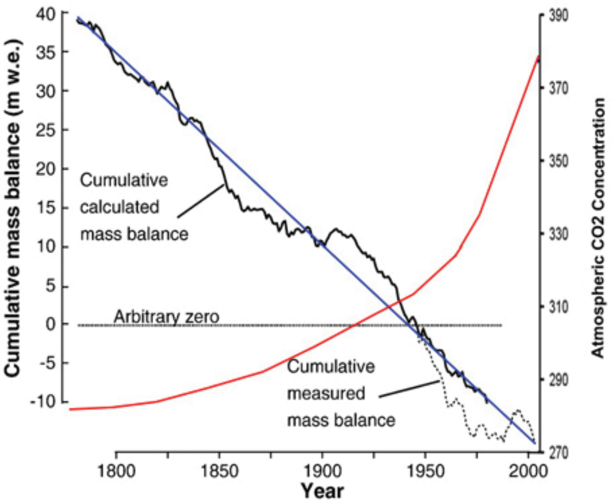

Figure 4.1.5.2. The cumulative reconstructed net mass balance (bN) history of Sweden's Storglaciaren, to which we have added the fit-by-eye descending linear relationship, in blue, and the history of the atmosphere's CO_2 concentration, in red. Adapted from Linderholm et al. (2007).

Additional evidence for post-LIA glacial expansion is provided by the history of the Solheimajokull outlet glacier on the southern coast of Iceland. In a review of its length over the past 300 years, Mackintosh *et al*. (2002) report a post-LIA minimum of 13.8 km in 1970, whereupon the glacier began to expand, growing to a length of about 14.3 km by 1995. The minimum length of 13.8 km observed in 1970 also did not eclipse an earlier minimum in which the glacier had decreased from a 300-year maximum length of 15.2 km in 1740 to a 300-year minimum of 13.2 km in 1783.

More recent glacial advances have been reported in Norway. According to Chin *et al*. (2005), glacial recession in Norway was most strongly expressed in "the middle of the 20th century," ending during the late 1950s to early 1960s." Then, "after some years with more or less stationary glacier front positions, [the glaciers] began to advance, accelerating in the late 1980s." Around 2000, a portion of the glaciers began to slow, while some even ceased moving; but they say that "most of the larger outlets with longer reaction times are continuing to advance." Chin *et al*. report that "the distances regained and the duration of this recent advance episode are both far greater than any previous readvance since the Little Ice Age maximum, making the recent resurgence a significant event." Mass balance data reveal much the same thing, "especially since 1988" and "at all [western] maritime glaciers in both southern and northern Norway," where "frequent above-average winter balances are a main cause of the positive net balances at the maritime glaciers during the last few decades."

In considering the results of the studies summarized above, it appears there is no correlation between atmospheric CO_2 levels and glacier melting or advancement in Europe. Several European glaciers are holding their own or actually advancing over the past quarter-century, a period of time in which the IPCC claims the earth has warmed to its highest temperature of the past thousand 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/europegla. php.

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4.1.6. North America

The history of North American glacial activity also fails to support the claim that anthropogenic CO_2 emissions are causing glaciers to melt. Dowdeswell *et al.* (1997) analyzed the mass balance histories of the 18 Arctic glaciers with the longest observational records, finding that just over 80 percent of them displayed negative mass balances over the last half of the twentieth century. However, they note that "ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age." They say "there is no compelling indication of increasingly negative balance conditions which might, *a priori*, be expected from anthropogenically induced global warming."

Clague *et al.* (2004) documented glacier and vegetation changes at high elevations in the upper Bowser River basin in the northern Coast Mountains of British Columbia, based on studies of the distributions of glacial moraines and trimlines, tree-ring data, cores from two small lakes that were sampled for a variety of analyses (magnetic susceptibility, pollen, diatoms, chironomids, carbon and nitrogen content, ^{210}Pb, ^{137}Cs, ^{14}C), similar analyses of materials obtained from pits and cores from a nearby fen, and by accelerator mass spectrometry radiocarbon dating of plant fossils, including wood fragments, tree bark, twigs and conifer needles and cones. All this evidence suggested a glacial advance that began about 3,000 years ago and may have lasted for hundreds of years, which would have placed it within the unnamed cold period that preceded the Roman Warm Period. There was also evidence for a second minor phase of activity that began about 1,300 years ago but was of short duration, which would have placed it within the Dark Ages Cold Period. Finally, the third and most extensive Neoglacial interval began shortly after AD 1200, following the Medieval Warm Period, and ended in the late 1800s, which was, of course, the Little Ice Age, during which time Clague *et al.* say "glaciers achieved their greatest extent of the past 3,000 years and probably the last 10,000 years."

These data clearly depict the regular alternation between non-CO_2-forcecd multi-century cold and warm periods that is the trademark of the millennial-scale oscillation of climate that reverberates throughout glacial and interglacial periods alike. That a significant, but by no means unprecedented, warming followed the most recent cold phase of this cycle is in no way unusual, particularly since the Little Ice Age was likely the coldest period of the last 10,000 years.

Alaska, Calkin *et al.* (2001) reviewed the most current and comprehensive research of Holocene glaciation along the northernmost portion of the Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where several periods of glacial advance and retreat were noted during the past 7,000 years. Over the latter part of this record, there was a general glacial retreat during the Medieval Warm Period that lasted for a few centuries prior to A.D. 1200, after which there were three major intervals of Little Ice Age glacial advance: the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century. During these latter time periods, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers also "reached their Holocene maximum extensions."

Wiles *et al.* (2004) derived a composite Glacier Expansion Index (GEI) for Alaska based on "dendrochronologically derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens" for three climatically distinct regions—the Arctic Brooks Range, the southern transitional interior straddled by the Wrangell and St. Elias mountain ranges, and the Kenai, Chugach, and St. Elias coastal ranges—after which they compared this history of glacial activity with "the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability" and with the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

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

Wiles *et al*. said "increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries." They made no mention of possible CO_2-induced global warming in discussing their results, presumably because there was no need to do so. Alaskan glacial activity, which in their words "has been shown to be primarily a record of summer temperature change (Barclay *et al*., 1999)," appears to be sufficiently well described within the context of centennial (solar) and decadal (PDO) variability superimposed upon the millennial-scale (non-CO_2-forced) variability that produces longer-lasting Medieval Warm Period and Little Ice Age conditions.

Pederson *et al*. (2004) used tree-ring reconstructions of North Pacific surface temperature anomalies and summer drought as proxies for winter glacial accumulation and summer ablation, respectively, to create a 300-year history of regional glacial Mass Balance Potential (MBP), which they compared with historic retreats and advances of Glacier Park's extensively studied Jackson and Agassiz glaciers in northwest Montana..

As they describe it, "the maximum glacial advance of the Little Ice Age coincides with a sustained period of positive MBP that began in the mid-1770s and was interrupted by only one brief ablation phase (~1790s) prior to the 1830s," after which they report "the mid-19th century retreat of the Jackson and Agassiz glaciers then coincides with a period marked by strong negative MBP." From about 1850 onward, they note "Carrara and McGimsey (1981) indicate a modest retreat (~3-14 m/yr) for both glaciers until approximately 1917." At that point, they report that "the MBP shifts to an extreme negative phase that persists for ~25 yr," during which period the glaciers retreated "at rates of greater than 100 m/yr."

Continuing with their history, Pederson *et al*. report that "from the mid-1940s through the 1970s retreat rates slowed substantially, and several modest advances were documented as the North Pacific transitioned to a cool phase [and] relatively mild summer conditions also prevailed." From the late 1970s through the 1990s, they say, "instrumental records indicate a shift in the PDO back to warmer conditions resulting in continuous, moderate retreat of the Jackson and Agassiz glaciers."

The first illuminating aspect of this glacial history is that the post-Little Ice Age retreat of the Jackson and Agassiz glaciers began just after 1830, in harmony with the findings of a number of other studies from various parts of the world (Vincent and Vallon, 1997; Vincent, 2001, 2002; Moore *et al*., 2002; Yoo and D'Odorico, 2002; Gonzalez-Rouco *et al*. 2003; Jomelli and Pech, 2004), including the entire Northern Hemisphere (Briffa and Osborn, 2002; Esper *et al*., 2002). These findings stand in stark contrast to what is suggested by the IPCC-endorsed "hockeystick" temperature history of Mann *et al*. (1998, 1999), which does not portray *any* Northern Hemispheric warming until around 1910.

The second illuminating aspect of the glacial record is that the vast bulk of the glacial retreat in Glacier National Park occurred between 1830 and 1942, over which time the air's CO_2 concentration rose by only 27 ppm, which is less than a third of the total CO_2 increase experienced since the start of glacial recession. Then, from the mid-1940s through the 1970s, when the air's CO_2 concentration rose by another 27 ppm, Pederson *et al*. report that "retreat rates slowed substantially, and several modest advances were documented."

The first 27 ppm increase in atmospheric CO_2 concentration coincided with the great preponderance of glacial retreat experienced since the start of the warming that marked the "beginning of the end" of the Little Ice Age, but the next 27 ppm increase in the air's CO_2 concentration was accompanied by little if any additional glacial retreat, when, of course, there was little if any additional warming.

Something other than the historic rise in the air's CO_2 content was responsible for the disappearing ice fields of Glacier National Park. The historical behavior of North America's glaciers provides no evidence for unprecedented or unnatural CO_2-induced global warming over any part of 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/n/northamgla.php.

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4.1.7. South America

Harrison and Winchester (2000) used dendrochronology, lichenometry, and aerial photography to date nineteenth and twentieth century fluctuations of the Arco, Colonia, and Arenales glaciers on the eastern side of the Hielo Patagonico Norte in southern Chile. This work revealed that these glaciers, plus four others on the western side of the ice field, began to retreat, in the words of the two researchers, "from their Little Ice Age maximum positions" somewhere between 1850 and 1880, well before the air's CO_2 content began to rise at a significant rate. They also note that the trend continued "through the first half of the 20th century with various still-stands and oscillations between 1925 and 1960 ... with retreat increasing since the

1960s," just as has been observed at many sites in the Northern Hemisphere.

Glasser *et al*. (2004) described a large body of evidence related to glacier fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte and the Hielo Patagonico Sur. This evidence indicates that the most recent glacial advances in Patagonia occurred during the Little Ice Age. Prior to then, their data indicate an interval of higher temperatures known as the Medieval Warm Period, when glaciers decreased in size and extent; this warm interlude was in turn preceded by an era of pronounced glacial activity that is designated the Dark Ages Cold Period, which was also preceded by a period of higher temperatures and retreating glaciers that is denoted the Roman Warm Period.

Glasser *et al*. documented cycles of blacial advances and retreats each lasting hundreds of years going back to sometime between 6,000 and 5,000 ^{14}C years before present (BP). They cited the works of other scientists that reveal a similar pattern of cyclical glacial activity over the preceding millennia in several other locations. Immediately to the east of the Hielo Patagonico Sur in the Rio Guanaco region of the Precordillera, for example, they report that Wenzens (1999) detected five distinct periods of glacial advancement: "4500-4200, 3600-3300, 2300-2000, 1300-1000 ^{14}C years BP and AD 1600-1850." With respect to the glacial advancements that occurred during the cold interval that preceded the Roman Warm Period, they say they constitute "part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al*., 1998; Wasson and Claussen, 2002) which coincides with an abrupt decrease in solar activity," and they say that this observation was what "led van Geel *et al*. (2000) to suggest that variations in solar irradiance are more important as a driving force in variations in climate than previously believed."

Finally, with respect to the most recent recession of Hielo Patogonico Norte outlet glaciers from their late historic moraine limits at the end of the nineteenth century, Glasser *et al*. say that "a similar pattern can be observed in other parts of southern Chile (e.g., Kuylenstierna *et al*., 1996; Koch and Kilian, 2001)," to which we would also add the findings of Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al*. (2003) for the Bolivian Cordillera Real. Likewise, they note that "in areas peripheral to the North Atlantic and in central Asia the available evidence shows that glaciers underwent significant recession at this time (cf. Grove, 1988; Savoskul, 1997)."

Georges (2004) constructed a twentieth century history of glacial fluctuations in the Cordillera Blanca of Peru, which is the largest glaciated area within the tropics. This history reveals, in Georges words, that "the beginning of the century was characterized by a glacier recession of unknown extent, followed by a marked readvance in the 1920s that nearly reached the Little Ice Age maximum." Then came the "very strong" 1930s-1940s glacial mass *shrinkage*, after which there was a period of quiescence that was followed by an "intermediate retreat from the mid-1970s until the end of the century."

In comparing the two periods of glacial wasting, Georges says that "the intensity of the 1930s-1940s retreat was more pronounced than that of the one at the end of the century." In fact, his graph of the ice area lost in both time periods suggests that the rate of wastage in the 1930s-1940s was *twice as great* as that of last two decades of the twentieth century.

Georges is quite at ease talking about the Little Ice Age south of the equator in Peru, which is a very long way from the lands that border the North Atlantic Ocean, which is the only region on earth where the IPCC is willing to admit the existence of this chilly era of the planet's climatic history. The glacial extensions of the Cordillera Blanca in the late 1920s were almost equivalent to those experienced there during the depths of the Little Ice Age.

Koch and Kilian (2005) mapped and dated, by dendrochronological means, a number of moraine systems of Glaciar Lengua and neighboring glaciers of Gran Campo Nevado in the southernmost Andes of Chile, after which they compared their results with those of researchers who studied the subject in other parts of South America. According to their findings, in the Patagonian Andes "the culmination of the Little Ice Age glacier advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Rothlisberger, 1986; Aniya, 1996)," but "various glaciers at Hielo Patagonico Norte and Hielo Patagonico Sur also formed prominent moraines around 1870 and 1880 (Warren and Sugden, 1993; Winchester *et al*., 2001; Luckman and Villalba, 2001)." In addition, they note their study "further supports this scenario," and that from their observations at Glaciar Lengua and neighboring glaciers at Gran Campo Nevado, it would appear that "the 'Little Ice Age' advance was possibly the most extensive one during the Holocene for this ice cap."

Working with biogenic silica, magnetic susceptibility, total organic carbon (TOC), total nitrogen (TN), δ^{13}CTOC, δ^{15}NTN, and C/N ratios derived from the sediment records of two Venezuelan watersheds, which they obtained from cores retrieved from Lakes Mucubaji and Blanca, together with ancillary data obtained from other studies that had been conducted in the same general region, Polissar *et al.* (2006) developed continuous decadal-scale histories of glacier activity and moisture balance in that part of the tropical Andes (the Cordillera de Merida) over the past millennium and a half, from which they were able to deduce contemporary histories of regional temperature and precipitation.

The international team of scientists—representing Canada, Spain, the United States, and Venezuela—write that "comparison of the Little Ice Age history of glacier activity with reconstructions of solar and volcanic forcing suggests that solar variability is the primary underlying cause of the glacier fluctuations," because (1) "the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and δ^{14}C measurements," (2) "spectral analysis shows significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, closely matching the de Vreis and Gleissberg oscillations identified from solar irradiance reconstructions," and (3) "solar and volcanic forcing are uncorrelated between AD 1520 and 1650, and the magnetic susceptibility record follows the solar-irradiance reconstruction during this interval." In addition, they write that "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima," and that "temperature declines of -3.2 ± 1.4°C and precipitation increases of ~20% are required to produce the observed glacial responses."

In discussing their findings, Polissar *et al.* say their results "suggest considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability." The six scientists also say their findings imply "even greater probable responses to future anthropogenic forcing," and that "profound climatic impacts can be predicted for tropical montane regions."

With respect to these latter ominous remarks, we note that whereas Polissar *et al.*'s linking of significant climate changes with solar radiation variability is a factual finding of their work, their latter statements with respect to hypothesized CO_2-induced increases in down-welling thermal radiation are speculations that need not follow from what they learned.

Another point worth noting in this regard is Polissar *et al.*'s acknowledgement that "during most of the past 10,000 years, glaciers were absent from all but the highest peaks in the Cordillera de Merida," which indicates that warmer-than-present temperatures are the norm for this part of the planet, and that any significant warming that might yet occur in this region (as well as most of the rest of the world) would mark only a return to more typical Holocene (or current interglacial) temperatures, which have themselves been significantly lower than those of all four prior interglacials. What is more, atmospheric CO_2 concentrations were much lower during all of those much warmer periods.

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

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4.2. Sea Ice

A number of claims have been made that CO_2-induced global warming is melting sea ice in the Arctic and Antarctic and that such melting will accelerate as time passes. In this section we analyze Antarctic and Arctic sea ice trends as reported in the scientific literature. We revisit the issue of ice melting in much greater depth in Section 4.5.

4.2.1. Antarctic

Utilizing Special Sensor Microwave Imager (SSM/I) data obtained from the Defense Meteorological Satellite Program (DMSP) for the period December 1987-December 1996, Watkins and Simmonds (2000) analyzed temporal trends in different measures of the sea ice that surrounds Antarctica, noting that "it has been suggested that the Antarctic sea ice may show high sensitivity to any anthropogenic increase in temperature," and that most climate models predict that "any rise in surface temperature would result in a decrease in sea ice coverage."

Contrary to what one would expect on the basis of these predictions, the two scientists observed statistically significant *increases* in both sea ice area and sea ice extent over the period studied; and when they combined their results with results for the preceding period of 1978-1987, both parameters continued to show increases over the sum of the two periods (1978-1996). In addition, they determined that the 1990s also experienced increases in the length of the sea ice season.

Watkins and Simmonds' findings, i.e., that Southern Ocean sea ice has increased in area, extent, and season length since at least 1978, are supported by other studies. Hanna (2001) published an updated analysis of Antarctic sea ice cover based on SSM/I data for the period October 1987-September 1999, finding the serial sea ice data depict "an ongoing slight but significant hemispheric increase of 3.7(±0.3)% in extent and 6.6(±1.5)% in area." Parkinson (2002) utilized satellite passive-microwave data to calculate and map the length of the sea-ice season throughout the Southern Ocean for each year of the period 1979-1999, finding that although there are opposing regional trends, a "much larger area of the Southern Ocean experienced an overall lengthening of the sea-ice season … than experienced a shortening." Updating the analysis two years later for the period November 1978 through

December 2002, Parkinson (2004) reported a linear increase in 12-month running means of Southern Ocean sea ice extent of 12,380 ± 1,730 km_2 per year.

Zwally *et al*. (2002) also utilized passive-microwave satellite data to study Antarctic sea ice trends. Over the 20-year period 1979-1998, they report that the sea ice extent of the entire Southern Ocean increased by 11,181 ± 4,190 square km per year, or by 0.98 ± 0.37 percent per decade, while sea ice area increased by nearly the same amount: 10,860 ± 3,720 square km per year, or by 1.26 ± 0.43 percent per decade. They observed that the variability of monthly sea ice extent declined from 4.0 percent over the first 10 years of the record, to 2.7 percent over the last 10 years.

Yuan and Martinson (2000) analyzed Special SSM/I data together with data derived from brightness temperatures measured by the Nimbus-7 Scanning Multichannel Microwave Radiometer. Among other things, they determined that the mean trend in the latitudinal location of the Antarctic sea ice edge over the prior 18 years was an equatorward expansion of 0.011 degree of latitude per year.

Vyas *et al*. (2003) analyzed data from the multi-channel scanning microwave radiometer carried aboard India's OCEANSAT-1 satellite for the period June 1999-May 2001, which they combined with data for the period 1978-1987 that were derived from space-based passive microwave radiometers carried aboard earlier Nimbus-5, Nimbus-7, and DMSP satellites to study secular trends in sea ice extent about Antarctica over the period 1978-2001. Their work revealed that the mean rate of change of sea ice extent for the entire Antarctic region over this period was an increase of 0.043 M km^2 per year. In fact, they concluded that "the increasing trend in the sea ice extent over the Antarctic region may be slowly accelerating in time, particularly over the last decade," noting that the "continually increasing sea ice extent over the Antarctic Southern Polar Ocean, along with the observed decreasing trends in Antarctic ice surface temperature (Comiso, 2000) over the last two decades, is paradoxical in the global warming scenario resulting from increasing greenhouse gases in the atmosphere."

In a somewhat similar study, Cavalieri *et al*. (2003) extended prior satellite-derived Antarctic sea ice records several years by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite datasets with National Ice Center digital sea ice data, finding that sea ice extent about the continent increased at a mean rate of $0.10 \pm 0.05 \times 10^6$ km^2 per decade between 1977 and 2002. Likewise, Liu *et al*. (2004) used sea ice concentration data retrieved from the scanning multichannel microwave radiometer on the Nimbus 7 satellite and the spatial sensor microwave/imager on several defense meteorological satellites to develop a quality-controlled history of Antarctic sea ice variability covering the period 1979-2002, which includes different states of the Antarctic Oscillation and several ENSO events, after which they evaluated total sea ice extent and area trends by means of linear least-squares regression. They found that "overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (~4,801 km^2/yr)." In addition, they determined that "the total Antarctic sea ice area (the cumulative area of the ocean actually covered by at least 15% ice concentrations) has increased significantly by ~13,295 km^2/yr, exceeding the 95% confidence level," noting that "the upward trends in the total ice extent and area are robust for different cutoffs of 15, 20, and 30% ice concentrations (used to define the ice extent and area)."

Elderfield and Rickaby (2000) concluded that the sea ice cover of the Southern Ocean during glacial periods may have been as much as double the coverage of modern winter ice, suggesting that "by restricting communication between the ocean and atmosphere, sea ice expansion also provides a mechanism for reduced CO_2 release by the Southern Ocean and lower glacial atmospheric CO_2."

Three papers on Antarctic sea ice were published in 2008. Laine (2008) determined 1981-2000 trends of Antarctic sea-ice concentration and extent, based on the Scanning Multichannel Microwave Radiometer (SSMR) and SSM/I for the spring-summer period of November/December/ January. These analyses were carried out for the continent as a whole, as well as five longitudinal sectors emanating from the south pole: 20°E-90°E, 90°E-160°E, 160°E-130°W, 130°W-60°W, and 60°W-20°E. Results indicated that "the sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero." Laine also reports that "the Antarctic region as a whole and all the sectors separately show slightly positive spring-summer albedo trends."

Comiso and Nishio (2008) set out to provide updated and improved estimates of trends in Arctic and Antarctic sea ice cover for the period extending from November 1978 to December 2006, based on data obtained from the Advanced Microwave

Scanning Radiometer (AMSR-E), the SSM/I, and the SMMR, where the data from the last two instruments were adjusted to be consistent with the AMSR-E data. Their findings indicate that sea ice extent and area in the Antarctic grew by +0.9 ± 0.2 and +1.7 ± 0.3 percent per decade, respectively.

A study that "extends the analyses of the sea ice time series reported by Zwally *et al*. (2002) from 20 years (1979-1998) to 28 years (1979-2006)" by Cavalieri and Parkinson (2008) derived new linear trends of Antarctic sea ice extent and area based on satellite-borne passive microwave radiometer data. Results indicate "the total Antarctic sea ice extent trend increased slightly, from 0.96 ± 0.61 percent per decade to 1.0 ± 0.4 percent per decade, from the 20- to 28-year period," noting the latter trend is significant at the 95 percent confidence level. Corresponding numbers for the Antarctic sea ice area trend were 1.2 ± 0.7 percent per decade and 1.2 ± 0.5 percent per decade. Both sets of results indicate a "tightening up" of the two relationships: Over the last eight years of the study period, both the extent and area of Antarctic sea ice have continued to increase, with the former parameter increasing at a more rapid rate than it did over the 1979-1998 period.

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

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4.2.2. Arctic

Arctic climate is incredibly complex, varying simultaneously on a number of different timescales for a number of different reasons (Venegas and Mysak, 2000). Against this backdrop of multiple causation and timeframe variability, it is difficult to identify a change in either the extent or thickness of Arctic sea ice that could be attributed to the increase in temperature that has been predicted to result from the burning of fossil fuels. The task is further complicated because many of the records that do exist contain only a few years to a few decades of data, and they yield different trends depending on the period of time studied.

4.2.2.1. Extent

Johannessen *et al.* (1999) analyzed Arctic sea ice extent over the period 1978-1998 and found it to have decreased by about 14 percent. This finding led them to suggest that "the balance of evidence," as small as it then was, indicates "an ice cover in transition," and that "if this apparent transformation continues, it may lead to a markedly different ice regime in the Arctic," as was also suggested by Vinnikov *et al.* (1999).

Reading Johannessen *et al.*'s assessment of the situation, one is left with the impression that a relatively consistent and persistent reduction in the area of Arctic sea ice is in progress. However, and according to their own data, that assessment is highly debatable and possibly false. In viewing their plots of sea ice area, for example, it is readily evident that the decline in this parameter did not occur smoothly over the 20-year period of study. In fact, essentially all of the drop it experienced occurred abruptly over a single period of not more than three years (87/88-90/91) and possibly only one year (89/90-90/91). Furthermore, it could be argued from their data that from 1990/91 onward, sea ice area in the Arctic may have actually *increased*.

Support for this assessment of the data is found in Kwok (2004), who estimated "the time-varying perennial ice zone (PIZ) coverage and construct[s] the annual cycles of multiyear (MY, including second year) ice coverage of the Arctic Ocean using QuikSCAT backscatter, MY fractions from RADARSAT, and the record of ice export from satellite passive microwave observations" for the years 1999-2003. Kwok calculated the coverage of Arctic MY sea ice at the beginning of each year of the study was 3774 x 10^3 km^2 in 2000, 3896 x 10^3 km^2 in 2001, 4475 x 10^3 km^2 in 2002, and 4122 x 10^3 km^2 in 2003, representing an *increase* in sea ice coverage of 9 percent over a third of a decade.

More questions are raised Parkinson (2000b), who utilized satellite-derived data of sea ice extent to calculate changes in this parameter for the periods 1979-1990 and 1990-1999. He reports that in seven of the nine regions into which he divided the Arctic for his analysis, the "sign of the trend reversed from the 1979-1990 period to the 1990-1999 period," indicative of the ease with which significant decadal trends are often reversed in this part of the world.

In another study, Belchansky *et al.* (2004) report that from 1988 to 2001, total January multiyear ice area declined at a mean rate of 1.4 percent per year. In the autumn of 1996, however, they note that "a large multiyear ice recruitment of over 10^6 km^2 fully replenished the previous 8-year decline in total area." They add that the replenishment "was followed by an accelerated and compensatory decline during the subsequent 4 years." In addition, they learned that 75 percent of the interannual variation in January multiyear sea area "was explained by linear regression on two atmospheric parameters: the previous winter's Arctic Oscillation index as a proxy to melt duration and the previous year's average sea level pressure gradient across the Fram Strait as a proxy to annual ice export."

Belchansky *et al.* conclude that their 14-year analysis of multiyear ice dynamics is "insufficient to project long-term trends." They also conclude it is insufficient to reveal "whether recent declines in multiyear ice area and thickness are indicators of anthropogenic exacerbations to positive feedbacks that will lead the Arctic to an unprecedented future of reduced ice cover, or whether they are simply ephemeral expressions of natural low frequency oscillations." It should be noted in this regard, however, that low frequency oscillations are what the data actually reveal; and such behavior is not what one would predict from a gradually increasing atmospheric CO_2 concentration.

In another study, Heide-Jorgensen and Laidre (2004) examined changes in the fraction of open-water found within various pack-ice microhabitats of Foxe Basin, Hudson Bay, Hudson Strait, Baffin Bay-Davis Strait, northern Baffin Bay, and Lancaster Sound over a 23-year interval (1979-2001) using remotely sensed microwave measurements of sea-ice extent, after which the trends they documented were "related to the relative importance of each wintering microhabitat for eight marine indicator species and potential impacts on winter success and survival were examined."

Results of the analysis indicate that Foxe Basin, Hudson Bay, and Hudson Strait showed small increasing trends in the fraction of open-water, with the upward trends at all microhabitats studied ranging from 0.2 to 0.7 percent per decade. In Baffin Bay-Davis Straight and northern Baffin Bay, on the other hand, the open-water trend was *downward*, and at a mean rate for all open-water microhabitats studied of fully 1 percent per decade, while the trend in all Lancaster Sound open-water microhabitats was also downward, in this case at a mean rate of 0.6 percent per decade.

With respect to the context of these open-water declines, Heide-Jorgensen and Laidre report that "increasing trends in sea ice coverage in Baffin Bay and Davis Strait (resulting in declining open-water) were as high as 7.5 percent per decade between 1979-1999 (Parkinson *et al*., 1999; Deser *et al*., 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002) and comparable significant increases have been detected back to 1953 (Stern and Heide-Jorgensen, 2003)." They additionally note that "similar trends in sea ice have also been detected locally along the West Greenland coast, with slightly lower increases of 2.8 percent per decade (Stern and Heide-Jorgensen, 2003)."

Cavalieri *et al*. (2003) extended prior satellite-derived Arctic sea ice records several years back in time by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite datasets via comparisons with National Ice Center digital sea ice data. For the newly extended period of 1972-2002, they determined that Arctic sea ice extent had declined at a mean rate of $0.30 \pm 0.03 \times 10^6$ km^2 per decade; while for the shortened period from 1979-2002, they found a mean rate of decline of $0.36 \pm 0.05 \times 10^6$ km^2 per decade, or at a rate that was 20 percent greater than the full-period rate. In addition Serreze *et al*. (2002) determined that the downward trend in Arctic sea ice extent during the passive microwave era culminated with a record minimum value in 2002.

These results could readily be construed to indicate an increasingly greater rate of Arctic sea ice melting during the latter part of the twentieth century. However, the results of these studies are not the end of the story. As Grumet *et al*. (2001) have described the situation, recent trends in Arctic sea ice cover "can be viewed out of context because their brevity does not account for interdecadal variability, nor are the records sufficiently long to clearly establish a climate trend."

In an effort to overcome this "short-sightedness," Grumet *et al*. developed a 1,000-year record of spring sea ice conditions in the Arctic region of Baffin Bay based on sea-salt records from an ice core obtained from the Penny Ice Cap on Baffin Island. In doing so, they determined that after a period of reduced sea ice during the eleventh through fourteenth centuries, enhanced sea ice conditions prevailed during the following 600 years. For the final (twentieth) century of this period, however, they report that "despite warmer temperatures during the turn of the century, sea-ice conditions in the Baffin Bay/Labrador Sea region, at least during the last 50 years, are within 'Little Ice Age' variability," suggesting that sea ice extent there has not yet emerged from the range of conditions characteristic of the Little Ice Age.

In an adjacent sector of the Arctic, this latter period of time was also studied by Comiso *et al*. (2001), who used satellite imagery to analyze and quantify a number of attributes of the Odden ice tongue—a winter ice-cover phenomenon that occurs in the Greenland Sea with a length of about 1,300 km and an aerial coverage of as much as 330,000 square kilometers—over the period 1979-1998. By utilizing surface air temperature data from Jan Mayen Island, which is located within the region of study, they were able to infer the behavior of this phenomenon over the past 75 years. Trend analyses revealed that the ice tongue has exhibited no statistically significant change in any of the parameters studied over the past 20 years; but the proxy reconstruction of the Odden ice tongue for the past 75 years revealed the ice phenomenon to have been "a relatively smaller feature several decades ago," due to the warmer temperatures that prevailed at that time.

In another study of Arctic climate variability, Omstedt and Chen (2001) obtained a proxy record of the annual maximum extent of sea ice in the region of the Baltic Sea over the period 1720-1997. In analyzing this record, they found that a significant decline in sea ice occurred around 1877. In addition, they reported finding greater variability in sea ice extent in the colder 1720-1877 period than in the warmer 1878-1997 period.

Also at work in the Baltic Sea region, Jevrejeva (2001) reconstructed an even longer record of sea ice duration (and, therefore, extent) by examining historical data for the observed time of ice break-up between 1529 and 1990 in the northern port of Riga, Latvia. The long date-of-ice-break-up time series was best described by a fifth-order polynomial, which identified four distinct periods of climatic transition: (1) 1530-1640, warming with a tendency toward earlier ice break-up of nine days/century, (2) 1640-1770, cooling with a tendency toward later ice break-up of five days/century, (3) 1770-1920, warming with a tendency toward earlier ice break-up of 15 days/century, and (4) 1920-1990, *cooling* with a tendency toward later ice break-up of 12 days/century.

On the other hand, in a study of the Nordic Seas (the Greenland, Iceland, Norwegian, Barents, and Western Kara Seas), Vinje (2001) determined that "the extent of ice in the Nordic Seas measured in April has decreased by 33% over the past 135 years." He notes, however, that "nearly half of this reduction is observed over the period 1860-1900," and we note, in this regard, that the first half of this sea-ice decline occurred over a period of time when the atmosphere's CO_2 concentration rose by only 7 ppm, whereas the second half of the sea-ice decline occurred over a period of time when the air's CO_2 concentration rose by more than 70 ppm. If the historical rise in the air's CO_2 content has been responsible for the historical decrease in sea-ice extent, its impact over the last century has declined to less than a tenth of what its impact was over the preceding four decades. This in turn suggests that the increase in the air's CO_2 content over the past 135 years has likely had nothing to do with the concomitant decline in sea-ice cover.

In a similar study of the Kara, Laptev, East Siberian, and Chuckchi Seas, based on newly available long-term Russian observations, Polyakov *et al.* (2002) found "smaller than expected" trends in sea ice cover that, in their words, "do not support the hypothesized polar amplification of global warming." Likewise, in a study published the following year, Polyakov *et al.* (2003) report that "over the entire Siberian marginal-ice zone the century-long trend is only -0.5% per decade," while "in the Kara, Laptev, East Siberian, and Chukchi Seas the ice extent trends are not large either: -1.1%, -0.4%, +0.3%, and -1.0% per decade, respectively." Moreover, they say "these trends, except for the Chukchi Sea, are not statistically significant."

Divine and Dick (2006) used historical April through August ice observations made in the Nordic Seas—comprised of the Iceland, Greenland, Norwegian, and Barents Seas, extending from 30°W to 70°E—to construct time series of ice-edge position anomalies spanning the period 1750-2002, which they analyzed for evidence of long-term trend and oscillatory behavior. The authors report that "evidence was found of oscillations in ice cover with periods of about 60 to 80 years and 20 to 30 years, superimposed on a continuous negative trend," which observations are indicative of a "persistent ice retreat since the second half of the 19th century" that began well before anthropogenic CO_2 emissions could have had much effect on earth's climate.

Noting that the last cold period observed in the Arctic occurred at the end of the 1960s, the two Norwegian researchers say their results suggest that "the Arctic ice pack is now at the periodical apogee of the low-frequency variability," and that "this could explain the strong negative trend in ice extent during the last decades as a possible superposition of natural low frequency variability and greenhouse gas induced warming of the last decades." However, as they immediately caution, "a similar shrinkage of ice cover was observed in the 1920s-1930s, during the previous warm phase of the low frequency oscillation, when any anthropogenic influence is believed to have still been negligible." They suggest, therefore, "that during decades to come … the retreat of ice cover may change to an expansion."

In light of this litany of findings, it is difficult to accept the claim that Northern Hemispheric sea ice is rapidly disintegrating in response to CO_2-induced global warming. Rather, the oscillatory behavior observed in so many of the sea ice studies suggests, in the words of Parkinson (2000b), "the possibility of close connections between the sea ice cover and major oscillatory patterns in the atmosphere and oceans," including connections with: "(1) the North Atlantic Oscillation (e.g., Hurrell and van Loon, 1997; Johannessen *et al*., 1999; Kwok and Rothrock, 1999; Deser *et al*., 2000; Kwok, 2000, Vinje, 2001) and the spatially broader Arctic Oscillation (e.g., Deser *et al*., 2000; Wang and Ikeda, 2000); (2) the Arctic Ocean Oscillation (Polyakov *et al*., 1999; Proshutinsky *et al*., 1999); (3) a 'see-saw' in winter temperatures between Greenland and northern Europe (Rogers and van Loon, 1979); and (4) an interdecadal Arctic climate cycle (Mysak *et al*., 1990; Mysak and Power, 1992)." The likelihood that Arctic sea ice trends are the product of such natural oscillations, Parkinson continues, "provides a strong rationale for considerable caution when extrapolating into the future the widely reported decreases in the Arctic ice cover over the past few decades or when attributing the decreases primarily to global warming," a caution with which we heartily agree.

One final study of note is that of Bamber *et al.* (2004), who used high-accuracy ice-surface elevation measurements (Krabill *et al*., 2000) of the largest ice cap in the Eurasian Arctic—Austfonna, on the island of Nordaustlandet in northeastern Svalbard—to evaluate ice cap elevation changes between 1996 and 2002. They determined that the central and highest-altitude area of the ice cap, which comprises 15 percent of its total area, "increased in elevation by an average of 50 cm per year between 1996 and 2002," while "to the northeast of this region, thickening of about 10 cm per year was also observed." They further note that the highest of these growth rates represents "as much as a 40% increase in accumulation rate (Pinglot *et al*., 2001)."

Based on the ancillary sea-ice and meteorological data they analyzed, Bamber *et al.* concluded that the best explanation for the dramatic increase in ice cap growth over the six-year study period was a large increase in precipitation caused by a concomitant reduction in sea-ice cover in this sector of the Arctic. Their way of characterizing this phenomenon is simply to say that it represents the transference of ice from the top of the sea (in this case, the Barents Sea) to the top of the adjacent land (in this case, the Austfonna ice cap). And as what has been observed to date is only the beginning of the phenomenon, which will become even stronger in the absence of nearby sea-ice, "projected changes in Arctic sea-ice cover," as they say in the concluding sentence of their paper, "will have a significant impact on the mass-balance of land ice around the Arctic Basin over at least the next 50 years." Which result, we might add, may be just the opposite of that forecast by 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/s/seaicearctic.php.

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4.2.2.2. Thickness

Based on analyses of submarine sonar data, Rothrock *et al*. (1999) suggested that Arctic sea ice in the mid 1990s had thinned by about 42 percent of the average 1958-1977 thickness. The IPCC reports the Rothrock finding but then reports that other more recent studies found “the reduction in ice thickness was not gradual, but occurred abruptly before 1991,” and acknowledges that “ice thickness varies considerably from year to year at a given location and so the rather sparse temporal sampling provided by submarine data makes inferences regarding long term change difficult” (IPCC 2007, p. 353). Johannessen *et al.* (1999), for example, found that essentially all of the drop occurred rather abruptly over a single period of not more than three years (1987/88-1990/91) and possibly only one year (1989/90-1990/91).

Two years after Johannessen *et al.*, Winsor (2001) analyzed a more comprehensive set of Arctic sea-ice data obtained from six submarine cruises conducted between 1991 and 1997 that had covered the central Arctic Basin from 76° N to 90° N, as well as two areas that had been particularly densely sampled, one centered at the North Pole (>87° N) and one in the central part of the Beaufort Sea (centered at approximately 76° N, 145°W). The transect data across the entire Arctic Basin revealed that the mean Arctic sea-ice thickness had remained “almost constant” over the period of study. Data from the North Pole also showed little variability, and a linear regression of the data revealed a “slight increasing trend for the whole period.” As for the Beaufort Sea region, annual variability in sea ice thickness was greater than at the North Pole but once again, in Winsor’s words, “no significant trend” in mean sea-ice thickness was found. Combining the North Pole results with the results of an earlier study, Winsor concluded that “mean ice thickness has remained on a near-constant level around the North Pole from 1986 to 1997.”

The following year, Holloway and Sou (2002) explored “how observations, theory, and modeling work together to clarify perceived changes to Arctic sea ice,” incorporating data from “the atmosphere, rivers, and ocean along with dynamics expressed in an ocean-ice-snow model.” On the basis of a number of different data-fed model runs, they found that for the last half of the past century, “no linear trend [in Arctic sea ice volume] over 50 years is appropriate,” noting their results indicated “increasing volume to the mid-1960s, decadal variability without significant trend from the mid-1960s to the mid-1980s, then a loss of volume from the mid-1980s to the mid-1990s.” The net effect of this behavior, in their words, was that “the volume estimated in 2000 is close to the volume estimated in 1950.” They suggest that the initial inferred rapid thinning of Arctic sea ice was, as they put it, “unlikely,” due to problems arising from under-sampling. They also report that “varying winds that readily redistribute Arctic ice create a recurring pattern whereby ice shifts between the central Arctic and peripheral regions, especially in the Canadian sector,” and that the “timing and tracks of the submarine surveys missed this dominant mode of variability.”

In the same year, Polyakov *et al.* (2002) employed newly available long-term Russian landfast-ice data obtained from the Kara, Laptev, East Siberian, and Chuckchi Seas to investigate trends and variability in the Arctic environment poleward of 62°N. This study revealed that fast-ice thickness trends in the different seas were “relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level.” A year later, these results were reconfirmed by Polyakov *et al.* (2003), who reported that the available fast-ice records “do not show a significant trend,” while noting that “in the Kara and Chukchi Seas trends are positive, and in the Laptev and East Siberian Seas trends are negative,” but stating that “these trends are not statistically significant at the 95% confidence level.”

Laxon *et al.* (2003) used an eight-year time series (1993-2001) of Arctic sea-ice thickness data derived from measurements of ice freeboard made by radar altimeters carried aboard ERS-1 and 2 satellites to determine the mean thickness and variability of Arctic sea ice between latitudes 65° and 81.5°N, which region covers the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. These real-world observations (1) revealed “an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models,” (2) undermined “the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent,” and (3) showed that “sea ice mass can change by up to 16% within one year,” which finding “contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming.” Laxon *et al.* concluded that “errors are present in current simulations of Arctic sea ice,” stating in their closing sentence that “until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and future, changes in Arctic ice cover will be open to question.”

Pfirman *et al.* (2004) analyzed Arctic sea-ice drift dynamics from 1979-1997, based on monthly fields of ice motion obtained from the International Arctic Buoy Program, using a Lagrangian perspective that “shows the complexities of ice drift response to variations in atmospheric conditions.” This analysis indicated that “large amounts of sea ice form over shallow Arctic shelves, are transported across the central basin and are exported primarily through Fram Strait and, to lesser degrees, the Barents Sea and Canadian Archipelago,” consistent with the observations of several other investigators. They also determined that within the central Arctic, ice travel times averaged 4.0 years from 1984-85 through 1988-89, but only 3.0 years from 1990-91 through 1996-97. This enhanced rate of export of old ice to Fram Strait from the Beaufort Gyre over the latter period decreased the fraction of thick-ridged ice within the central basin of the Arctic, and was deemed by Pfirman *et al.* to be responsible for some of the sea-ice thinning observed between the 1980s and 1990s. They also note that the rapid change in ice dynamics that occurred between 1988 and 1990 was “in response to a weakening of the Beaufort high pressure system and a strengthening of the European Arctic low (a shift from lower North Atlantic Oscillation/Arctic Oscillation to higher NAO/OA index) [Walsh *et al*., 1996; Proshutinsky and Johnson, 1997; Kwok, 2000; Zhang *et al*., 2000; Rigor *et al*., 2002].”

Lastly, in a paper on landfast ice in Canada’s Hudson Bay, Gagnon and Gough (2006) cite nine different studies of sea-ice cover, duration, and thickness in the Northern Hemisphere, noting that the Hudson Bay region “has been omitted from those studies with the exception of Parkinson *et al*. (1999).” For 13 stations located on the shores of Hudson Bay (seven) and surrounding nearby lakes (six), Gagnon and Gough then analyzed long-term weekly measurements of ice thickness and associated weather conditions that began and ended, in the mean, in 1963 and 1993, respectively.

Results of the study revealed that a "statistically significant thickening of the ice cover over time was detected on the western side of Hudson Bay, while a slight thinning lacking statistical significance was observed on the eastern side." This asymmetry, in their words, was "related to the variability of air temperature, snow depth, and the dates of ice freeze-up and break-up," with "increasing maximum ice thickness at a number of stations" being "correlated to earlier freeze-up due to negative temperature trends in autumn," and with high snow accumulation being associated with low ice thickness, "because the snow cover insulates the ice surface, reducing heat conduction and thereby ice growth." Noting that their findings "are in contrast to the projections from general circulation models, and to the reduction in sea-ice extent and thickness observed in other regions of the Arctic," Gagnon and Gough say "this contradiction must be addressed in regional climate change impact assessments."

These observations suggest that much of the reported thinning of Arctic sea ice that occurred in the 1990s—if real, as per Winsor (2001)—was not the result of CO_2-induced global warming. Rather, it was a natural consequence of changes in ice dynamics caused by an atmospheric regime shift, of which there have been several in decades past and will likely be several in decades to come, irrespective of past or future changes in the air's CO_2 content. Whether any portion of possible past sea ice thinning was due to global warming is consequently still impossible to know, for temporal variability in Arctic sea-ice behavior is simply too great to allow such a small and slowly developing signal to be detected yet. In describing an earlier regime shift, for example, Dumas *et al*. (2003) noted that "a sharp decrease in ice thickness of roughly 0.6 m over 4 years (1970-74) [was] followed by an abrupt increase of roughly 0.8 m over 2 years (1974-76)."

It will likely be a number of years before anything definitive can be said about CO_2-induced global warming on the basis of the thickness of Arctic sea-ice, other than that its impact on sea-ice thickness is too small to be detected at the present time.

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

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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 δ^{18}O proxy record of monsoon rainfall intensity as recorded in calcite δ^{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 δ^{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 δ^{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 global representation," as their combined drainage basins represent about 55 percent of the land area draining into the global ocean. In the words of the five researchers, "between 1951 and 2000 cumulative discharge for the 137 rivers remained statistically unchanged." In addition, they report that "global on-land precipitation between 1951 and 2000 remained statistically unchanged." Then, in a simple and straightforward conclusion, Milliman *et al*. write that "neither discharge nor precipitation changed significantly over the last half of the 20th century, offering little support to a global intensification of the hydrological cycle," such as is generally claimed to be a consequence of CO_2-induced global warming.

In the rest of this section we review studies for Eurasia and North America, seeking to discover if there have been any twentieth century changes in streamflow regimes that might reasonably have been caused by twentieth century changes in air temperature and atmospheric CO_2 concentration. Additional information on this topic, including reviews on streamflow not discussed here, can be found at http://www.co2science.org/subject/s/subject_s.php under the heading Streamflow.

Reference

Milliman, J.D., Farnsworth, K.L., Jones, P.D., Xu, K.H. and Smith, L.C. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. *Global and Planetary Change* **62**: 187-194.

4.4.1. Eurasia

Pederson *et al*. (2001) used tree-ring chronologies from northeastern Mongolia to develop annual precipitation and streamflow histories for the period 1651-1995. This work revealed, with respect to both standard deviations and five-year intervals of extreme wet and dry periods, that "variations over the recent period of instrumental data are not unusual relative to the prior record," although they say that the reconstructions "appear to show more frequent extended wet periods in more recent decades." Nevertheless, they state 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 of 12 and 20-24 years, suggesting, in the researchers' words, "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Working in another part of the same region, Davi *et al*. (2006) report that "absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia were used in precipitation models and an individual model was made using the longest of the five tree-ring records (1340-2002)," which effort led to a reconstruction of streamflow that extended from 1637 to 1997. In analyzing these data, the four researchers 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 covered the period from 1937 to 2003. In addition, they report 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 evidence that the warming of the twentieth century has led to increased variability in precipitation and streamflow.

Pekarova *et al*. (2003) analyzed the annual discharge rates of selected large rivers of the world for recurring cycles of wet and dry periods. For those rivers with sufficiently long and accurate data series, they also derived long-term discharge rate trends. This latter analysis did not show "any significant trend change in long-term discharge series (1810-1990) in representative European rivers," including the Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone, and Po. These latter observations are most interesting, for they indicate that even over the 180-year time period that saw the demise of the Little Ice Age and the ushering in of the Current Warm Period, there were no long-term trends in the discharge rates of the major rivers of Europe.

In another study, Hisdal *et al*. (2001) performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and frequency of drought over the following four time periods: 1962-1990, 1962-1995, 1930-1995, and 1911-1995. This protocol indicated 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 discovering that the number of trends pointing towards decreasing streamflow deficits or fewer drought events exceeded the number of trends pointing towards increasing streamflow deficits or more drought events.

Looking back towards Asia, Cluis and Laberge (2001) utilized 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 recent changes in river runoff of the type predicted by IPCC scenarios of global warming, such as increased streamflow and increases in streamflow variability that would lead to more floods and droughts. Spatially, their study encompassed 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region," while temporally the mean start and end dates of the river flow records were 1936 ± 5 years and 1988 ± 1 year.

As a result of their analyses, the two researchers determined that mean river discharges were unchanged in 67 percent of the cases investigated; where trends did exist 69 percent of them were downward. Likewise, maximum river discharges were unchanged in 77 percent of the cases investigated; where trends did exist 72 percent of them were downward. Minimum river discharges, on the other hand, were unchanged in 53 percent of the cases investigated; where trends did exist, 62 percent of them were upward. All six metrics related to streamflow trends exhibit changes contrary to IPCC-promoted scenarios of climate change.

In another study, MacDonald *et al*. (2007) used "tree ring records from a network of sites extending across northern Eurasia to provide reconstructions [extending back to AD 1800] of annual discharge for the October to September water year for the major Eurasian rivers entering the Arctic Ocean (S. Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma)." Results indicated that annual discharges of the mid to late twentieth century previously reported are not significantly greater than discharges experienced over the preceding 200 years, and "are thus still within the range of long-term natural variability." In addition, they say their "longer-term discharge records do not indicate a consistent positive significant correlation between discharge [and] Siberian temperature." They report there are actually weak *negative* correlations between discharge and temperature on some of the rivers over the period of their study.

In a contemporaneous study, Smith *et al*. (2007) present "a first analysis of a new dataset of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia," focusing on providing "a first continental-scale assessment of low-flow trends since the 1930s." Results indicate that "a clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or 'low flows,' have risen in northern Eurasia during the 20th century," adding that "from 12 unusually complete records from 1935-2002 we see that the minimum flow increases are greatest since ~1985."

Smith *et al*. reveals that over much of northern Eurasia, predictions of more drought seem rather off the mark, as daily low flows of the majority of northern Eurasian rivers have been *increasing*. Moreover, in the words of the five researchers, they have been increasing "in summer as well as winter and in non-permafrost as well as permafrost terrain," with the greatest increases occurring "since ~1985."

Writing about the Qinghai-Tibet Plateau, where they conducted their streamflow study, Cao *et al*. (2006) note that "both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature (Houghton *et al*., 2001; Rahmstorf and Ganopolski, 1999; Bruce *et al*., 2002)," stating that in these scenarios "under global warming, mainly in the middle and west regions of northwest China, precipitation increases significantly," so that "some researchers [have] even advanced the issue of [a] climatic shift from warm-dry to warm-wet in northwest China (Shi, 2003)," with the ultimate expectation that total river discharge within the region would significantly increase in response to global warming.

As a test of these climate-model predictions, Cao *et al*. analyzed annual discharge data for five large rivers of the Qinghai-Tibet Plateau over the period 1956-2000, using the Mann-Kendall nonparametric trend test; and in doing so, they found that over the period of their study, "river discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the Northern Hemisphere surface air temperature." Because they could detect "no increase in the stream discharge in the Qinghai-Tibet Plateau with global warming," Cao *et al*. concluded that their real-world findings are not "in accordance with the anticipated ideas" that led them to conduct their study. Indeed, the disconnect between streamflow and global warming in this and many other studies argues strongly against the claimed consequences of global warming, the claimed magnitude of global warming, or both of these standard claims.

Worried about the possibility that enhanced freshwater delivery to the Arctic ocean by increased river flow could shut down the ocean's thermohaline circulation, Peterson *et al*. (2002) plotted annual values of the combined discharge of the six largest Eurasian Arctic rivers (Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina)—which drain about two-thirds of the Eurasian Arctic landmass—against the globe's mean annual surface air temperature (SAT), after which they ran a simple linear regression through the data and determined that the combined discharge of the six rivers seems to rise by about 212 km^3/year in response to a 1°C increase in mean global air temperature. Then, they calculated that for the high-end global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) to occur by AD 2100, i.e., a temperature increase of 5.8°C, the warming-induced increase in freshwater discharge from the six rivers could rise by as much as 1260 km^3/year (we calculate 5.8°C x 212 km^3/year/°C = 1230 km^3/year), which represents a 70 percent increase over the mean discharge rate of the past several years.

The link between this conclusion and the postulated shutting down of the thermohaline circulation of the world's oceans resides in the hypothesis that the delivery of such a large addition of freshwater to the North Atlantic Ocean may slow—or even stop—that location's production of new deep water, which constitutes one of the driving forces of the great oceanic "conveyor belt." Although still discussed, this scenario is currently not as highly regarded as it was when Peterson *et al*. conducted their research, for a number of reasons. One that we have highlighted is the difficulty of accepting the tremendous extrapolation Peterson *et al*. make in extending their Arctic freshwater discharge vs. SAT relationship to the great length that is implied by the IPCC's predicted high-end warming of 5.8°C over the remainder of the current century. Consider, for example, that "over the period of the discharge record, global SAT increased by 0.4°C," according to Peterson *et al*. It is implausible to extend the relationship they derived across that small temperature range fully 14-and-a-half times further, to 5.8°C.

Consider also the Eurasian river discharge anomaly vs. global SAT plot of Peterson *et al*. (their Figure 4), which we have replotted in Figure 4.4.1. Enclosing their data with simple straight-line upper and lower bounds, it can be seen that the upper bound of the data does not change over the entire range of global SAT variability, suggesting the very real possibility that the upper bound corresponds to a maximum Eurasian river discharge rate that cannot be exceeded in the real world under its current geographic and climatic configuration. The lower bound, on the other hand, rises so rapidly with increasing global SAT that the two bounds intersect less than two-tenths of a degree above the warmest of Peterson et al.'s 63 data points, suggesting that 0.2°C beyond the temperature of their warmest data point may be all the further any relationship derived from their data may validly be extrapolated.

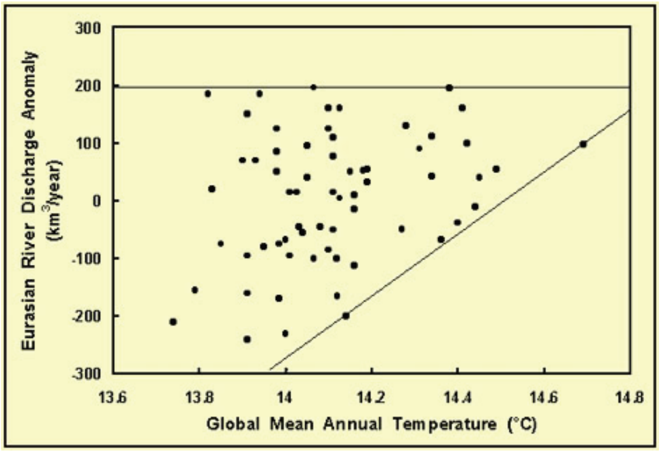

Figure 4.4.1. Annual Eurasian Arctic river discharge anomaly vs. annual global surface air temperature (SAT) over the period 1936 to 1999. Adapted from Peterson et al. (2002).

Clearly, real-world data do not support the hydrologic negativism the IPCC associates with both real-world and simulated global warming in Eurasia.

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

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4.4.2. North America

Brown *et al*. (1999) studied siliciclastic sediment grain size, planktonic foraminiferal and pteropod relative frequencies, and the carbon and oxygen isotopic compositions of two species of planktonic foraminifera in cored sequences of hemipelagic muds deposited over the past 5,300 years in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow characteristics over this time period. The results of their research indicated the occurrence of large megafloods—which they describe as having been "almost certainly larger than historical floods in the Mississippi watershed"—at 4,700, 3,500, 3,000, 2,500, 2,000, 1,200, and 300 years before present. These fluvial events, in their estimation, were likely "episodes of multidecadal duration," spawned by an export of extremely moist gulf air to midcontinental North America driven by naturally occurring same-time-scale oscillations in Gulf of Mexico ocean currents. These particular extreme events were in no way related to variations in atmospheric CO_2 concentration, as they occurred over a period of near-constancy in this atmospheric property.

Hidalgo *et al*. (2000) used a form of principal components analysis to reconstruct a history of streamflow in the Upper Colorado River Basin from information obtained from tree-ring data, after which they compared their results with the streamflow reconstruction of Stockton and Jacoby (1976). In doing so, they found their results were similar to those of the earlier 1976 study, but that their newer reconstruction responded with better fidelity to periods of below-average streamflow or regional drought, making it easier for them to see there had been "a near-centennial return period of extreme drought events in this region," going all the way back to the early 1500s. Hidalgo *et al*.'s work provided additional evidence for the existence of past droughts that surpassed the worst of the twentieth century.

Woodhouse *et al*. (2006) generated updated proxy reconstructions of water-year streamflow for four key streamflow gauges in the Upper Colorado River Basin (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona), "using an expanded tree-ring network and longer calibration records than in previous efforts." By these means they determined 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." Their work revealed that "longer duration droughts have occurred in the past," and "the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906-1995 average."

"Overall," in the words of the three researchers, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." They conclude that "droughts more severe than any 20th to 21st century event [have] occurred in the past." This finding is just the opposite of what the IPCC would have us believe.

Woodhouse and Lukas (2006) developed "a network of 14 annual streamflow reconstructions, 300-600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies." The results indicated that "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries." The authors note that "paleoclimatic studies indicate that the natural variability in 20th century [streamflow] gage records is likely only a subset of the full range of natural variability," while citing in support of this statement the studies of Stockton and Jacoby (1976), Smith and Stockton (1981), Meko *et al*. (2001), and Woodhouse (2001). Of greatest significance in this regard was probably the fact that "multi-year drought events more severe than the 1950s drought have occurred," and that "the greatest frequency of extreme low flow events occurred in the 19th century," with a "clustering of extreme event years in the 1840s and 1850s."

Working in an adjacent region of the western United States, Carson and Munroe (2005) used tree-ring data collected by Stockton and Jacoby (1976) from the Uinta Mountains of Utah to reconstruct mean annual discharge in the Ashley Creek watershed for the period 1637 to 1970. Significant persistent departures from the long-term mean were noted throughout the 334-year record of reconstructed streamflow. The periods 1637-1691 and 1741-1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows, indicative of persistent drought or near-drought conditions. By contrast, there was an overall abundance of extremely large flows and relatively few extremely small flows during the periods 1692-1740 and 1898-1945, indicative of wetter conditions.

Lins and Slack (1999) analyzed secular trends in streamflow for 395 climate-sensitive stream gage stations (including data from more than 1,500 individual gages) located throughout the conterminous United States, some of which stations possessed datasets stretching all the way back to 1914. They found many more up-trends than down-trends in streamflow nationally, with slight decreases "only in parts of the Pacific Northwest and the Southeast." These and other of their findings, as they describe them, indicate "the conterminous U.S. is getting wetter, but less extreme," and it is difficult to conceive of a better result. As the world has warmed over the past century, the United States has gotten wetter in the mean, but less variable at the extremes, where floods and droughts occur.

Also studying the conterminous United States were McCabe and Wolock (2002), who for the period 1895-1999 evaluated (1) precipitation minus annual potential evapotranspiration, (2) the surplus water that eventually becomes streamflow, and (3) the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. This exercise revealed there was a statistically significant increase in the first two of these parameters, while for the third there was no change, indicative of the fact that water has actually become more available within the conterminous United States, and there has been no increase in the amount of water required for optimum plant growth.

Knox (2001) studied how conversion of the U.S. Upper Mississippi River Valley from prairie and forest to crop and pasture land by settlers in the early 1800s influenced subsequent watershed runoff and soil erosion rates. Initially, the conversion of the region's natural landscape to primarily agricultural use boosted surface erosion rates to values three to eight times greater than those characteristic of pre-settlement times. In addition, the land-use conversion increased peak discharges from high-frequency floods by 200 to 400 percent. Since the late 1930s, however, surface runoff has been decreasing. The decrease "is not associated with climatic causes," according to Knox, who reports that "an analysis of temporal variation in storm magnitudes for the same period showed no statistically significant trend."

Other notable findings of Knox's study include the observation that since the 1940s and early 1950s, the magnitudes of the largest daily flows have been decreasing at the same time that the magnitude of the average daily baseflow has been increasing, indicating a trend toward fewer flood and drought conditions. Once again, we have a situation where global warming has coincided with a streamflow trend that is leading to the best of all possible worlds: one of greater water availability, but with fewer and smaller floods and droughts.

Molnar and Ramirez (2001) conducted a detailed watershed-based analysis of precipitation and streamflow trends for the period 1948-97 in a semiarid region of the southwestern United States, the Rio Puerco Basin of New Mexico. "At the annual timescale," as they describe it, "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 at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale; monthly totals increased in *low*-flow months and decreased in high-flow months.

Shifting to a study of snowmelt runoff (SMR), McCabe and Clark (2005) note that most prior studies of this phenomenon in the western United States have depended on trend analyses to identify changes in timing, but they indicate that "trend analyses are unable to determine if a trend is gradual or a step change." This fact is crucial, they say, because when "changes in SMR timing have been identified by linear trends, there is a tendency to attribute these changes to global warming because of large correlations between linear trends in SMR timing and the increasing trend in global temperature." Therefore, using daily streamflow data for 84 stations in the western U.S., each with complete water-year information for the period 1950-2003, they conducted a number of analyses that enabled them to determine each station's mean streamflow trend over the past half century, as well as any stepwise changes that may have occurred in each data series.

As others before them had previously learned, the two researchers found that "the timing of SMR for many rivers in the western United States has shifted to earlier in the snowmelt season." However, they discovered that "the shift to earlier SMR has not been a gradual trend, but appears to have occurred as a step change during the mid-1980s," which shift was "related to a regional step increase in April-July temperatures during the mid-1980s." As a result, and after discussing various other possible reasons for what they had discovered, McCabe and Clark concluded that "the observed change in the timing of SMR in the western United States is a regional response to natural climatic variability and may not be related to global trends in temperature."

Over in Minnesota, Novotny and Stefan (2006) analyzed streamflow records (extending up to the year 2002, with lengths ranging from 53 to 101 years) obtained from 36 gauging stations in five major river basins of the state, deriving histories of seven annual streamflow statistics: "mean annual flow, 7-day low flow in winter, 7-day low flow in summer, peak flow due to snow melt runoff, peak flow due to rainfall, as well as high and extreme flow days (number of days with flow rates greater than the mean plus one or two standard deviations, respectively)." In doing so, they found significant trends in each of the seven streamflow statistics throughout the state, but that in most cases "the trends are not monotonic but periodic," and they determined, as might have been expected, that "the mean annual stream flow changes are well correlated with total annual precipitation changes."

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

The two researchers write that "an increase in mean annual streamflow in Minnesota would be welcome," as "it could provide more aquatic habitat, better water quality, and more recreational opportunities, among other benefits." Likewise, they say that "water quality and aquatic ecosystems should benefit from increases in low flows in both the summer and winter, since water quality stresses are usually largest during low flow periods." In addition, they say "other good news is that spring floods (from snowmelt), the largest floods in Minnesota, have not been increasing significantly."

Rood *et al*. (2005) performed an empirical analysis of streamflow trends for rivers fed by relatively pristine watersheds in the central Rocky Mountain Region of North America that extends from Wyoming in the United States through British

Columbia in Canada. They applied both parametric and non-parametric statistical analyses to assess nearly a century of annual discharge (ending about 2002) along 31 river reaches that drain this part of North America. These analyses revealed that river flows in this region *declined* over the past century by an average of 0.22 percent per year, with four of them exhibiting recent decline rates exceeding 0.5 percent per year. This finding, in the words of Rood *et al.*, "contrasts with the many current climate change predictions that [this] region will become warmer and wetter in the near-future."

Working entirely in Canada, where about three-quarters of the country is drained by rivers that discharge their water into the Arctic and North Atlantic Oceans, Déry and Wood (2005) analyzed hydrometric data from 64 northern Canadian rivers that drain more than half of the country's landmass for the period 1964-2003. Then, after assessing both variability and trends, they explored the influence of large-scale teleconnections as possible drivers of the trends they detected. This work indicated there was a statistically significant mean decline of approximately 10 percent in the discharge rates of the 64 rivers over the four decades of their study, which was nearly identical to the decline in precipitation falling over northern Canada between 1964 and 2000. These facts led the two scientists to conclude that the changes in river discharge they observed were driven "primarily by precipitation rather than evapotranspiration." As for the *cause* of the precipitation/river discharge decline, statistically significant links were found between the decline and the Arctic Oscillation, the El Niño/Southern Oscillation, and the Pacific Decadal Oscillation. Consequently, the results of this study indicate there is nothing unusual about the four-decade-long trends in northern Canada river discharge rates, which means there is nothing in these trends that would suggest a global warming impact.

Also in Canada, Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, to provide a non-vegetation-based high-resolution record of climate variability for this part of North America over the past 4,000 years. This research effort revealed the existence of periods of both increasing and decreasing grain size (a proxy for moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales. The most predominant departures included several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500-1900), the Medieval Warm Period (about AD 700-1300), the Dark Ages Cold Period (about BC 100 to AD 700), and the Roman Warm Period (about BC 900-100). In addition, a standardized median grain-size history revealed that the highest rates of stream discharge during the past 4,000 years occurred during the Little Ice Age approximately 300-350 years ago. During this 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, when median grain sizes were nearly 2 standard deviations below the 4,000-year mean, while most recently, grain size over the past 150 years has generally remained above average.

The Pine Lake sediment record convincingly demonstrates the reality of the non-CO_2-induced millennial-scale climatic oscillation that has alternately brought several-century-long periods of dryness and wetness to the southern Alberta region of North America during concomitant periods of relative global warmth and coolness, respectively, revealing a relationship that was not evident in the prior streamflow studies reviewed here that did not stretch all the way back in time to the Medieval Warm Period. It also demonstrates there is nothing unusual about the region's current moisture status.

In a final study from Canada, St. George (2007) begins by noting that the study of Burn (1994) suggested that a doubling of the air's CO_2 content could increase the severity and frequency of droughts in the prairie provinces of Canada (Alberta, Saskatchewan, Manitoba), but that results from an ensemble of climate models suggest that runoff in the Winnipeg River region of southern Manitoba, as well as runoff in central and northern Manitoba, could increase 20-30 percent by the middle of the twenty-first century (Milly *et al.*, 2005). To help resolve this dichotomy, St. George obtained daily and monthly streamflow data from nine gauge stations within the Winnipeg River watershed from the Water Survey of Canada's HYDAT data archive, plus precipitation and temperature data from Environment Canada's Adjusted Historical Canadian Climate Data archive, and analyzed them for trends over the period 1924-2003.

This work revealed, in the words of St. George, that "mean annual flows have increased by 58% since 1924 ... with winter streamflow going up by 60-110%," primarily because of "increases in precipitation during summer and autumn." In addition, he notes that similar "changes in annual and winter streamflow are observed in records from both regulated and unregulated portions of the watershed, which point to an underlying cause related to climate." Countering these positive findings, however, St. George says there are "reports of declining flow for many rivers in the adjacent Canadian prairies," citing the studies of Westmacott and Burn (1997), Yulianti and Burn (1998), Dery and Wood (2005), and Rood *et al*. (2005). Consequently, just as there are conflicting predictions about the future water status of portions of the prairie provinces of Canada, especially in Manitoba, so too are there conflicting reports about past streamflow trends in this region. It is anybody's guess as to what will actually occur in the years and decades ahead, although based on the observed trends he discovered, St. George believes "the potential threats to water supply faced by the Canadian Prairie Provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin."

Thus, we note there appear to be few real-world data that provide any significant support for the contention that CO_2-induced global warming will lead to more frequent and/or more severe increases and decreases in streamflow that result in, or are indicative of, more frequent and/or more severe floods and droughts. In the vast majority of cases, observed trends appear to be just the opposite of what is predicted to occur. Not only are real-world observations nearly all not undesirable, they are positive, and typically extremely so.

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

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4.5. Sea-level Rise

The possibility of large sea-level rises as a result of global warming is featured prominently in presentations of those, such as former U.S. Vice President Al Gore, who call for urgent action to "stop" global warming. In this section we examine historical trends in sea level to see if there is any indication of an increase in the mean rate-of-rise of the global ocean surface in response to the supposedly unprecedented warming of the planet over the course of the twentieth century. We then examine closely the various scenarios proposed whereby melting ice would cause sea levels to rise.

4.5.1 Mean Global Sea Levels

Cazenave *et al*. (2003) studied climate-related processes that cause variations in mean global sea level on interannual to decadal time scales, focusing on thermal expansion of the oceans and continental water mass balance. In doing so, they determined that the rate of thermal-induced sea-level rise over the past 40 years was about 0.5 mm/year. From early 1993 to the end of the twentieth century, however, analyses of TOPEX-Poseidon altimetry data and the global ocean temperature data of Levitus *et al*. (2000) yielded rates-of-rise that were approximately six times greater than the mean four-decade rate, which suggested to them that "an acceleration took place in the recent past, likely related to warming of the world ocean." However, as they alternatively note, "the recent rise may just correspond to the rising branch of a decadal oscillation." In addition, they say that "satellite altimetry and *in situ* temperature data have their own uncertainties and it is still difficult to affirm with certainty that sea-level rise is indeed accelerating." In fact, they cite the work of Nerem and Mitchum (2001) as indicating that "about 20 years of satellite altimetry data would be necessary to detect, with these data alone, any acceleration in sea-level rise."

Mörner (2004) provided a more expansive setting for his analysis of the subject by noting that "prior to 5000-6000 years before present, all sea-level curves are dominated by a general rise in sea level in true glacial eustatic response to the melting of continental ice caps," but that "sea-level records are now dominated by the irregular redistribution of water masses over the globe ... primarily driven by variations in ocean current intensity and in the atmospheric circulation system and maybe even in some deformation of the gravitational potential surface." With respect to the last 150 years, he reports that "the mean eustatic rise in sea level for the period 1850-1930 was [on] the order of 1.0-1.1 mm/year," but that "after 1930-40, this rise seems to have stopped (Pirazzoli *et al*., 1989; Mörner, 1973, 2000)." This stasis, in his words, "lasted, at least, up to the mid-60s." Thereafter, with the advent of the TOPEX/Poseidon mission, Mörner notes that "the record can be divided into three parts: (1) 1993-1996 with a clear trend of stability, (2) 1997-1998 with a high-amplitude rise and fall recording the ENSO event of these years and (3) 1998-2000 with an irregular record of no clear tendency." Most important of all, in his words, Mörner states "there is a total absence of any recent 'acceleration in sea-level rise' as often claimed by IPCC and related groups," and, therefore, "there is no fear of any massive future flooding as claimed in most global warming scenarios."

Church *et al*. (2004) used TOPEX/Poseidon satellite altimeter data to estimate global empirical orthogonal functions, which they combined with historical tide gauge data, to estimate monthly distributions of large-scale sea-level variability and change over the period 1950-2000. Their resultant "best estimate" of the rate of globally averaged sea-level rise over the last half of the twentieth century was 1.8 ± 0.3 mm/year. In addition, they noted that "decadal variability in sea level is observed, but to date there is no detectable secular increase in the rate of sea-level rise over the period 1950-2000." What is more, they reported that no increase in the rate of sea-level rise has been detected for the entire twentieth century, citing the work of Woodworth (1990) and Douglas (1992).

Cazenave and Nerem (2004) seemed to dismiss the caveats expressed in Cazenave *et al.* (2003) when they claimed that "the geocentric rate of global mean sea-level rise over the last decade (1993-2003) is now known to be very accurate, +2.8 ± 0.4 mm/year, as determined from TOPEX/Poseidon and Jason altimeter measurements," and that "this rate is significantly larger than the historical rate of sea-level change measured by tide gauges during the past decades (in the range of 1-2 mm/year)." However, they then admit "the altimetric rate could still be influenced by decadal variations of sea level unrelated to long-term climate change, such as the Pacific Decadal Oscillation, and thus a longer time series is needed to rule this out." They also noted that satellite altimetry had revealed a "non-uniform geographical distribution of sea-level change, with some regions exhibiting trends about 10 times the global mean." In addition, they note that "for the past 50 years, sea-level trends caused by change in ocean heat storage also show high regional variability," which fact "has led to questions about whether the rate of 20th-century sea-level rise, based on poorly distributed historical tide gauges, is really representative of the true global mean." Consequently, and in spite of the many new instruments and techniques that are being used to search for a global warming signal in global sea-level data, Cazenave and Nerem report that "these tools seem to have raised more questions than they have answered."

Noting that global climate models "show an increase in the rate of global average sea-level rise during the twentieth century," but that several prior studies (Douglas, 1991, 1992; Maul and Martin, 1993; Church *et al*., 2004; Holgate and Woodworth, 2004) had shown the measured rate of global sea-level rise to have been rather stable over the past hundred years, White *et al*. (2005) compared estimates of coastal and global averaged sea level for 1950 to 2000. Their results confirmed the earlier findings of "no significant increase in the rate of sea-level rise during this 51-year period."

Lombard *et al*. (2005) investigated the thermosteric or temperature-induced sea-level change of the past 50 years using the global ocean temperature data of Levitus *et al*. (2000) and Ishii *et al*. (2003). This work revealed that thermosteric sea-level variations are dominated by decadal oscillations of the planet's chief ocean-atmosphere climatic perturbations (El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation). In terms of the global mean, as they describe it, thermosteric trends computed over 10-year windows "show large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (-1 to -1.5 mm/year for the decade centered on 1980)." In the mean, however, and over the full half-century period Lombard *et al*. investigated, there was a net rise in sea level due to the thermal expansion of sea water, but only because the record began at the bottom of a trough and ended at the top of a peak. In between these two points, there were both higher and lower values, so one cannot be sure what would be implied if earlier data were available or what will be implied as more data are acquired. Noting that sea-level trends derived from TOPEX/Poseidon altimetry over 1993-2003 are "mainly caused by thermal expansion" and are thus "very likely a non-permanent feature," Lombard *et al.* conclude that "we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone." Even the 50 years of global ocean temperature data we possess are insufficient to tell us much about the degree of global warming that may have occurred over the past half-century, as any long-term increase in global sea level that may have been caused by the temperature increase is dwarfed by decadal-scale variability.

Carton *et al*. (2005) introduced their study of the subject by noting that "recent altimeter observations indicate an increase in the rate of sea-level rise during the past decade to 3.2 mm/year, well above the centennial estimate of 1.5-2 mm/year," noting further that "this apparent increase could have resulted from enhanced melting of continental ice or from decadal changes in thermosteric and halosteric effects." They explored these opposing options "using the new eddy-permitting Simple Ocean Data Assimilation version 1.2 reanalysis of global temperature, salinity, and sea level spanning the period 1968-2001." They determined that "the effect on global sea-level rise of changing salinity is small except in subpolar regions." However, they found that warming-induced steric effects "are enough to explain much of the observed rate of increase in the rate of sea-level rise in the last decade of the twentieth century without need to invoke acceleration of melting of continental ice."

And as determined by Lombard *et al*., as described in the preceding paragraph, the high thermosteric-induced rate-of-rise of global sea level over the past decade is likely “a non-permanent feature” of the global ocean’s transient thermal behavior. Consequently, and in harmony with the findings of Levitus *et al*. (2005) and Volkov and van Aken (2005), Carton *et al*. found no need to invoke the melting of land-based glacial ice to explain the observed increase in global sea-level rise of the past decade.

Even more revealing was the globally distributed sea-level time series study of Jevrejeva *et al*. (2006), who analyzed information contained in the Permanent Service for Mean Sea Level database using a method based on Monte Carlo Singular Spectrum Analysis and removed 2- to 30-year quasi-periodic oscillations to derive nonlinear long-term trends for 12 large ocean regions, which they combined to produce the mean global sea level (gsl) and gsl rate-of-rise (gsl rate) curves depicted in Figure 4.5.1.1.

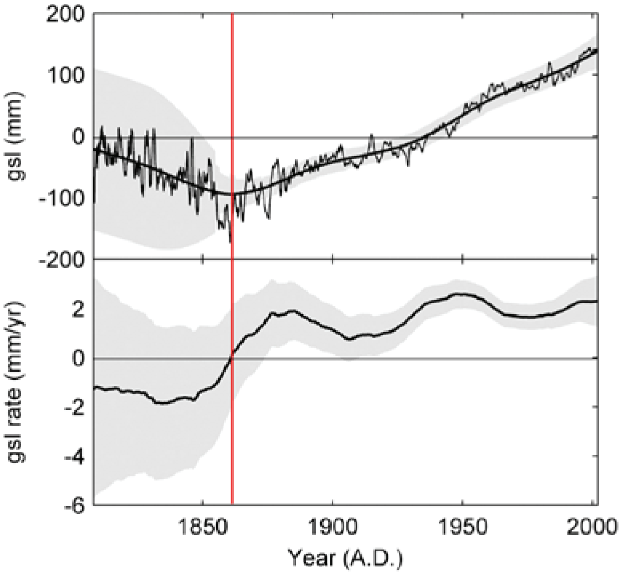

Figure 4.5.1.1. Mean global sea level (top), with shaded 95 percent confidence interval, and mean gsl rate-of-rise (bottom), with shaded standard error interval, adapted from Jevrejeva *et al.* (2006).

The figure clearly shows no acceleration of sea-level rise since the end of the Little Ice Age. Jevrejeva *et al*. say “global sea-level rise is irregular and varies greatly over time,” but “it is apparent that rates in the 1920-1945 period are likely to be as large as today’s.” In addition, they report that their “global sea-level trend estimate of 2.4 ± 1.0 mm/year for the period from 1993 to 2000 matches the 2.6 ± 0.7 mm/year sea-level rise found from TOPEX/Poseidon altimeter data.” With respect to what the four researchers describe as “the discussion on whether sea-level rise is accelerating,” their results pretty much answer the question in the negative.

The observations described above make us wonder why late twentieth century global warming—if it were as extreme as the IPCC claims it has been—cannot be detected in global sea-level data. The effects of the warming that led to the demise of the Little Ice Age—which the IPCC contends should have been considerably less dramatic than the warming of the late twentieth century—are readily apparent to the right of the vertical red line in the figure. Likewise, although the atmospheric CO_2 concentration experienced a dramatic increase in its rate-of-rise just after 1950 (shifting from a 1900-1950 mean rate-of-rise of 0.33 ppm/year to a 1950-2000 mean rate-of-rise of 1.17 ppm/year), the mean global sea-level rate-of-rise did not trend upwards after 1950, nor has it subsequently exceeded its 1950 rate-of-rise.

In concluding our examination of the peer-reviewed sea-level science, we report the findings of the most recent study of Holgate (2007). In a previous paper, Holgate and Woodworth (2004) derived a mean global sea-level history from 177 coastal tide gauge records that spanned the period 1955-1998. In an attempt to extend that record back in time another half-century, Holgate chose nine much longer high-quality records from around the world (New York, Key West, San Diego, Balboa, Honolulu, Cascais, Newlyn, Trieste, and Auckland) to see if their combined mean progression over the 1955-1998 period was similar enough to the concomitant mean sea-level history of the 177 stations to employ the mean nine-station record as a reasonable representation of mean global sea-level history for the much longer period stretching from 1904 to 2003.

In comparing the sea-level histories derived from the two datasets, Holgate found their mean rates-of-rise were indeed similar over the second half of the twentieth century; this observation thus implied, in Holgate’s words, that “a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to [do].”

As a result of this finding, Holgate constructed the nine-station-derived wavering line in Figure 4.5.1.2 as a reasonable best representation of the 1904-2003 mean global sea-level history of the world.

Based on that history, he calculated that the mean rate of global sea-level rise was "larger in the early part of the last century (2.03 ± 0.35 mm/year 1904-1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954-2003)."

Another way of thinking about the century-long sea-level history portrayed in Figure 4.5.1.2 is suggested by the curve we have fit to it, which indicates that mean global sea level may have been rising, in the mean, ever more slowly with the passage of time throughout the entire last hundred years.

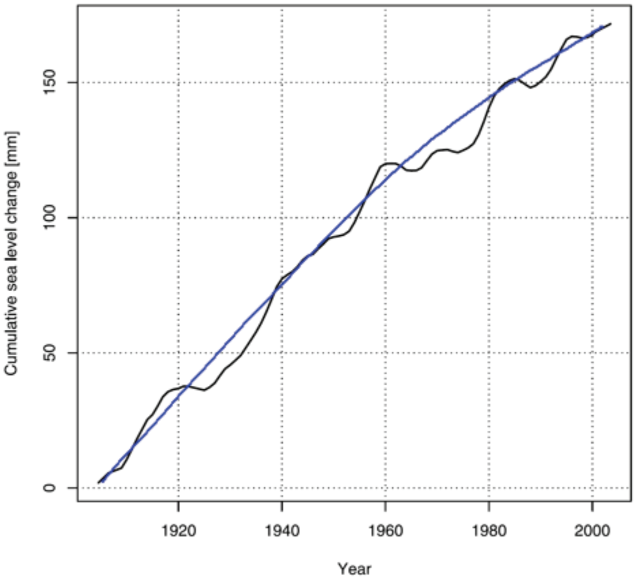

Figure 4.5.1.2. Cumulative increase in mean global sea level (1904-2003) derived from nine high-quality tide gauge records from around the world. Adapted from Holgate (2007).

Whichever way one looks at the findings of Holgate—either as two successive linear trends (representative of the mean rates-of-rise of the first and last halves of the twentieth century) or as one longer continuous curve (such as we have drawn)—the nine select tide gauge records indicate that the mean rate of global sea-level rise has *not* accelerated over the recent past, and has probably fallen.

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

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4.5.2. Antarctica Contribution to Sea Level

Vaughn *et al*. (1999) used more than 1,800 published and unpublished *in situ* measurements of the surface mass balance of Antarctica to produce an assessment of yearly ice accumulation over the continent. Their results indicated that the "total net surface mass balance for the conterminous grounded ice sheet is 1811 Gton yr^{-1} (149 kg m^{-2} yr^{-1}) and for the entire ice sheet including ice shelves and embedded ice rises, 2288 Gton yr^{-1} (166 kg m^{-2} yr^{-1})." These values, in their words, "are around 18% and 7% higher than the estimates widely adopted at present [1999]," which were derived about 15 years earlier. They suggest that net icefall on Antarctica may well have increased somewhat over that prior decade and a half. Nevertheless, because of uncertainties in the various numbers, Vaughn *et al*. say "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea-level change."

In another review of the subject that was published about the same time, Reeh (1999) found a broad consensus for the conclusion that a 1°C warming would create but little net change in mean global sea level. Greenland's contribution would be a sea-level rise on the order of 0.30 to 0.77 millimeters per year, while Antarctica's contribution would be a fall on the order of 0.20 to 0.70 millimeters per year.

The following year, Wild and Ohmura (2000) studied the mass balance of Antarctica using two general circulation models developed at the Max Planck Institute for Meteorology in Hamburg, Germany: the older ECHAM3 and the new and improved ECHAM4. Under a doubled atmospheric CO_2 scenario, the two models were in close agreement in their mass balance projections, with both of them predicting increases in ice sheet growth, indicative of decreases in sea level.

Two years later, van der Veen (2002) addressed the problem again, noting that "for purposes of formulating policies, some of which could be unpopular or costly, it is imperative that probability density functions be derived for predicted values such as sea-level rise," further stating that with "greater societal relevance comes increased responsibility for geophysical modelers to demonstrate convincingly the veracity of their models to accurately predict future evolution of the earth's natural system or particular components thereof." In stepping forward to perform this task with respect to sea-level change, however, he was forced to conclude that "the validity of the parameterizations used by [various] glaciological modeling studies to estimate changes in surface accumulation and ablation under changing climate conditions has not been convincingly demonstrated." Van der Veen calculated, for example, that uncertainties in model parameters are sufficiently great to yield a 95 percent confidence range of projected meltwater contributions from Greenland and Antarctica that encompass global sea-level lowering as well as rise by 2100 A.D. for low, middle, and high warming scenarios. Hence, even for the worst of the IPCC warming projections, there could well be little to no change in mean global sea level due to the likely rise in the air's CO_2 content that may occur over the rest of this century. As a result, van der Veen concludes that the confidence level that can be placed in current ice sheet mass balance models "is quite low." Paraphrasing an earlier assessment of the subject, he says today's best models "currently reside on the lower rungs of the ladder of excellence" and "considerable improvements are needed before accurate assessments of future sea-level change can be made."

Wadhams and Munk (2004) attempted "an independent estimate of eustatic sea-level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level)." Their analysis produced "a eustatic rise of only 0.6 mm/year," and when a steric contribution of 0.5 mm/year is added to the eustatic component, "a total of 1.1 mm/year, somewhat less than IPCC estimates," is the final result. Perhaps the most interesting finding of their analysis, however, is that the continental run-off which is "allowed," after subtracting the effect of sea ice melt, "is considerably lower than current estimates of sub-polar glacial retreat, suggesting a negative contribution from polar ice sheets (Antarctica plus Greenland) or from other non-glacial processes." In this regard, they assert "we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive *or* negative contribution."

The bottom line of Wadhams and Munk's analysis, as well as the other studies we have reviewed, is that there is considerable uncertainty associated with a number of basic parameters related to the water balance of the world's oceans and the meltwater contribution of Antarctica. Until these uncertainties are satisfactorily resolved, we cannot be confident that we know what is happening at the bottom of the world in terms of phenomena related to sea level.

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

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4.5.3. West Antarctic Ice Sheet

4.5.3.1. Collapse and Disintegration

The West Antarctic Ice Sheet (WAIS) is often described as the world's most unstable large ice sheet. As Hillenbrand *et al*. (2002) report, "it was speculated, from observed fast grounding-line retreat and thinning of a glacier in Pine Island Bay (Rignot, 1998; Shepherd *et al*., 2001), from the timing of late Pleistocene-Holocene deglaciation in the Ross Sea (Bindschadler, 1998; Conway *et al*., 1999), and from predicted activity of ice-stream drainage in response to presumed future global warming (Oppenheimer, 1998), that the WAIS may disappear in the future, causing the sea-level to rise at a rate of 1 to 10 mm/year (Bindschadler, 1998; Oppenheimer, 1998)."

Cofaigh *et al*. (2001) analyzed five sediment cores from the continental rise west of the Antarctic Peninsula and six from the Weddell and Scotia Seas for their ice rafted debris (IRD) content, in an attempt to see if there are Antarctic analogues of the Heinrich layers of the North Atlantic Ocean, which testify of the repeated collapse of the eastern margin of the Laurentide Ice Sheet and the concomitant massive discharge of icebergs. If such IRD layers exist around Antarctica, the researchers reasoned, they would be evidence of "periodic, widespread catastrophic collapse of basins within the Antarctic Ice Sheet," which could obviously occur again. However, after carefully studying their data, they concluded that "the ice sheet over the Antarctic Peninsula did not undergo widespread catastrophic collapse along its western margin during the late Quaternary," and they say this evidence "argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles." If there was no dramatic break-up of the WAIS over the last few glacial cycles, there's a very good chance there will be none before the current interglacial ends, especially since the data of

Petit *et al*. (1999) indicate that the peak temperatures of each of the previous four intergalcials were warmer than the peak temperature of the current interglacial by an average of more than 2°C.

Hillenbrand *et al*. (2002) studied the nature and history of glaciomarine deposits contained in sediment cores recovered from the West Antarctic continental margin in the Amundsen Sea to "test hypotheses of past disintegration of the WAIS." In doing so, they found that all proxies regarded as sensitive to a WAIS collapse changed markedly during the global climatic cycles of the past 1.8 million years, but they "do not confirm a complete disintegration of the WAIS during the Pleistocene" at a place where "dramatic environmental changes linked to such an event should be documented." They say their results "suggest relative stability rather than instability of the WAIS during the Pleistocene climatic cycles," and they note that this conclusion is "consistent with only a minor reduction of the WAIS during the last interglacial period," citing the work of Huybrechts (1990), Cuffey and Marshall (2000) and Huybrechts (2002).

In another paper that addresses the subject of possible WAIS collapse, O'Neill and Oppenheimer (2002) say the ice sheet "may have disintegrated in the past during periods only modestly warmer (~2°C global mean) than today," and they thus claim that setting "a limit of 2°C above the 1990 global average temperature"—above which the mean temperature of the globe should not be allowed to rise—"is justified." In fact, a 2°C warming of the globe would likely have little to no impact on the stability of the WAIS. The average Antarctic peak temperature of all four of the world's prior interglacials was at least 2°C greater than the Antarctic peak temperature of the current interglacial; yet, in the words of the scientists who developed the pertinent temperature record (Petit *et al*., 1999), the evidence contained in the core "makes it unlikely that the West Antarctic ice sheet collapsed during the past 420,000 years," pretty much the same conclusion that was drawn by Cofaigh *et al.*

In addition, we know from the Vostok ice core record that the peak Antarctic temperature of the most recent prior interglacial was fully 3°C warmer than the peak Antarctic temperature of the interglacial in which we presently live, yet the WAIS still did not disintegrate then. Furthermore, we know that throughout the long central portion of the current interglacial (when the most recent peak Antarctic temperature was reached), it was much warmer than it was in 1990, which is the year from which O'Neill and Oppenheimer's critical 2°C warming increment is measured; and this fact raises the 3°C temperature elevation of the last interglacial relative to the global temperature of 1990 to something on the order of 4° or 5°C, for which, again, there was no evidence of even a partial WAIS disintegration.

Finally, and in spite of the current interglacial's current relative coolness, the Vostok ice core data indicate that the current interglacial has been by far the longest stable warm period of the entire 420,000-year record, which suggests we are probably long overdue for the next ice age to begin, and that we may not have the "5 to 50 centuries" that O'Neill and Oppenheimer suggest could be needed to bring about the WAIS disintegration subsequent to the attainment of whatever temperature in excess of 4° or 5°C above the current global mean would be needed to initiate the process.

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

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4.5.3.2. Dynamics

The supposedly imminent demise of the West Antarctic Ice Sheet (WAIS) is what Al Gore apparently had in mind when warned that if "half of Antarctica melted or broke up and slipped into the sea, sea levels worldwide would increase by between 18 and 20 feet" (Gore 2006). A few scientists, as reported by Ackert (2003), believe we are witnessing the CO_2-induced "early stages of rapid ice sheet collapse, with potential near-term impacts on the world's coastlines." However, studies of the dynamics of various components of the WAIS suggest this is highly unlikely.

Bindschadler and Vornberger (1998) utilized satellite imagery taken since 1963 to examine spatial and temporal changes of Ice Stream B, which flows into the Ross Ice Shelf. The data indicated that since that time, the ice stream's width had increased by nearly 4 kilometers, at a rate that was, in their words, an "order of magnitude faster than models have predicted." However, they reported that the flow speed of the ice stream had decreased over this time period by about 50 percent, noting that "such high rates of change in velocity greatly complicate the calculation of mass balance of the ice sheet," and that such changes "do not resolve the overriding question of the stability of the West Antarctic Ice Sheet."

Bindschadler (1998) reviewed what was known about the WAIS and analyzed its historical retreat in terms of its grounding line and ice front. This work revealed that from the time of the Last Glacial Maximum to the present, the retreat of the WAIS's grounding line had been faster than that of its ice front, which resulted in an expanding Ross Ice Shelf. In fact, Bindschadler reported that "the ice front now appears to be nearly stable," although its grounding line appeared to be retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years. Such a retreat would indeed result in a sustained sea-level rise of 8 to 13 cm per century. However, even the smallest of these sea-level rates-of-rise would require, according to Bindschadler, "a large negative mass balance for all of West Antarctica," and there were no broad-based data to support that scenario.

Oppenheimer (1998) reviewed 122 studies that dealt with the stability of the WAIS and its effects on global sea level, concluding that "human-induced climate change may play a significant role in controlling the long-term stability of the West Antarctic Ice Sheet and in determining its contribution to sea-level change in the near future." Other of his statements, however, detract from this conclusion. He noted, for example, that the Intergovernmental Panel on Climate Change (IPCC) "estimated a zero Antarctic contribution to sea-level rise over the past century, and projected a small negative (about -1 cm) contribution for the twenty-first century." With respect to the state and behavior of the atmosphere and ocean above and around Antarctica, he acknowledged that "measurements are too sparse to enable the observed changes to be attributed to any such [human-induced] global warming." And in the case of sea-ice extent, he admitted "the IPCC assessment is that no trend has yet emerged."

Oppenheimer concluded his review with four scenarios of the future based upon various assumptions. One was that the WAIS will experience a sudden collapse that causes a 4-6 m sea-level rise within the coming century. However, he stated that this scenario "may be put aside for the moment, because no convincing model of it has been presented." A second scenario had the WAIS gradually disintegrating and contributing to a slow sea-level rise over two centuries, followed by a more rapid disintegration over the following 50 to 200 years. Once again, however, he noted that "progress on understanding [the] WAIS over the past two decades has enabled us to lower the relative likelihood of [this] scenario."

In another scenario, the WAIS takes 500-700 years to disappear, as it raises sea-level by 60-120 cm per century. Oppenheimer assesses the relative likelihood of this scenario to be the highest of all, "but with low confidence," as he puts it. Last is what occurs if ice streams slow, as a result of internal ice sheet readjustments, and the discharge of grounded ice decreases, which could well happen even if ice shelves thin and major fast-moving glaciers do not slow. In such a situation, he notes that "the Antarctic contribution to sea-level rise turns increasingly negative," i.e., sea level *falls*. And in commenting upon the suite of scenarios just described, Oppenheimer emphatically states that "it is not possible to place high confidence in any specific prediction about the future of WAIS."

Also writing in *Nature*, Bell *et al*. (1998) used aerogeophysical data to investigate processes that govern fast-moving ice streams on the WAIS. In conjunction with various models, these data suggested a close correlation between the margins of various ice streams and the underlying sedimentary basins, which appeared to act as lubricants for the overlying ice. The seven scientists suggested that the positions of ice-stream margins and their onsets were controlled by features of the underlying sedimentary basins. They concluded that "geological structures beneath the West Antarctic Ice Sheet have the potential to dictate the evolution of the dynamic ice system, modulating the influence of changes in the global climate system," although their work did not indicate what effect, if any, a modest rise in near-surface air temperature might have on this phenomenon.

Rignot (1998) reported on satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996, which were studied to determine whether or not this major ice stream in remote West Antarctica was advancing or retreating. The data indicated that the glacier's grounding line had retreated inland at a rate of 1.2 ± 0.3 kilometers per year over the four-year period of the study; Rignot suggested that this retreat may have been the result of a slight increase in ocean water temperature. Because the study had utilized only four years of data, however, questions concerning the long-term stability of the WAIS, in the words of the researcher, "cannot be answered at present." In addition, although the glacier's grounding line had been found to be retreating, subsequent satellite images suggested that the location of the ice front had remained stable.

Also in the journal *Science*, Conway *et al*. (1999) examined previously reported research, while conducting some of their own, dealing with the retreat of the WAIS since its maximum glacial extent some 20,000 years ago. In doing so, they determined that the ice sheet's grounding line remained near its maximum extent until about 10,000 years ago, whereupon it began to retreat at a rate of about 120 meters per year. This work also indicated that at the end of the twentieth century it was retreating at about the same rate, which suggests that if it continues to behave as it has in the past, complete deglaciation of the WAIS will occur in about 7,000 years. The researchers concluded that the modern-day grounding-line retreat of the WAIS is part of an ongoing recession that has been underway since the early to mid-Holocene, and that "it is not a consequence of anthropogenic warming or recent sea-level rise."

Stenoien and Bentley (2000) mapped the catchment region of Pine Island Glacier using radar altimetry and synthetic aperture radar interferometry, which they used to develop a velocity map that revealed a system of tributaries that channel ice from the catchment area into the fast-flowing glacier. Then, by combining the velocity data with information on ice thickness and snow accumulation rates, they were able to calculate, within an uncertainty of 30 percent, that the mass balance of the catchment region was not significantly different from zero.

One year later, Shepherd *et al*. (2001) used satellite altimetry and interferometry to determine the rate of change of the ice thickness of the entire Pine Island Glacier drainage basin between 1992 and 1999. This work revealed that the grounded glacier thinned by up to 1.6 meters per year between 1992 and 1999. Of this phenomenon, the researchers wrote that "the thinning cannot be explained by short-term variability in accumulation and must result from glacier dynamics," and since glacier dynamics typically respond to phenomena operating on time scales of hundreds to thousands of years, this observation would argue against twentieth century warming being a primary cause of the thinning. Shepherd *et al*. additionally say they could "detect no change in the rate of ice thinning across the glacier over a 7-year period," which also suggests that a long-term phenomenon of considerable inertia must be at work in this particular situation.

But what if the rate of glacier thinning, which sounds pretty dramatic, were to continue unabated? The researchers state that "if the trunk continues to lose mass at the present rate it will be entirely afloat within 600 years." And if that happens, they "estimate the net contribution to eustatic sea level to be 6 mm," which means that over each century, we could expect global sea level to rise by about one millimeter, about the thickness of a paper clip.

Publishing in the same year were Pudsey and Evans (2001), who studied ice-rafted debris obtained from four cores in Prince Gustav Channel, which until 1995 was covered by floating ice shelves. Their efforts indicated that the ice shelves had also retreated in mid-Holocene time, but that, in their words, "colder conditions after about 1.9 ka allowed the ice shelf to reform." Although they concluded that the ice shelves are sensitive indicators of regional climate change, they were careful to state that "we should not view the recent decay as an unequivocal indicator of anthropogenic climate change." Indeed, the disappearance of the ice shelves was not unique; it had happened before without our help, and it could well have happened again on its own. In fact, the breakup of the Prince Gustav Channel ice shelves was likely nothing more than the culmination of the Antarctic Peninsula's natural recovery from the cold conditions of Little Ice Age.

Raymond (2002) presented a brief appraisal of the status of the world's major ice sheets. His primary conclusions relative to the WAIS were that (1) "substantial melting on the upper surface of WAIS would occur only with considerable atmospheric warming," (2) of the three major WAIS drainages, the ice streams that drain northward to the Amundsen Sea have accelerated, widened, and thinned "over substantial distances back into the ice sheet," but that "the eastward drainage toward the Weddell Sea is close to mass balance." And (3) of the westward drainage into the Ross Ice Shelf, "over the last few centuries, margins of active ice streams migrated inward and outward," while the "overall mass balance has changed from loss to gain," as "a currently active ice stream (Whillans) has slowed by about 20% over recent decades."

In a summary statement that takes account of these observations, Raymond says that "the total mass of today's ice sheets is changing only slowly, and even with climate warming increases in snowfall should compensate for additional melting," such as might possibly occur for the WAIS if the planet's temperature continues its post-Little Ice Age rebound.

Stone *et al*. (2003)—working on western Marie Byrd Land—report how they determined cosmogenic ^{10}Be exposure dates of glacially transported cobbles in elevation transects on seven peaks of the Ford Ranges between the ice sheet's present grounding line and the Clark Mountains some 80 km inland. Based on these ages and the elevations at which the cobbles were found, they reconstructed a history of ice-sheet thinning over the past 10,000-plus years. This history showed, in their words, that "the exposed rock in the Ford Ranges, up to 700 m above the present ice surface, was deglaciated within the past 11,000 years," and that "several lines of evidence suggest that the maximum ice sheet stood considerably higher than this."

Stone *et al*. additionally report that the consistency of the exposure age versus elevation trends of their data "indicates steady deglaciation since the first of these peaks emerged from the ice sheet some time before 10,400 years ago," and that the mass balance of the region "has been negative throughout the Holocene." The researchers also say their results "add to the evidence that West Antarctic deglaciation continued long after the disappearance of the Northern Hemisphere ice sheets and may still be under way," noting that the ice sheet in Marie Byrd Land "shows the same pattern of steady Holocene deglaciation as the marine ice sheet in the Ross Sea," where ice "has thinned and retreated since 7000 years ago," adding that "there is strong evidence that the limit of grounded ice in both regions—and in Pine Island Bay—is still receding."

The work of Stone *et al*. convincingly demonstrates that the current thinning and retreat of the WAIS are merely manifestations of a slow but steady deglaciation that has been going on ever since the beginning-of-the-end of the last great ice age. Stone *et al*. say "the pattern of recent change is consistent with the idea that thinning of the WAIS over the past few thousand years is continuing," while Ackert (2003) makes the point even plainer when he says "recent ice sheet dynamics appear to be dominated by the ongoing response to deglacial forcing thousands of years ago, rather than by a recent anthropogenic warming or sea-level rise."

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

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4.5.3.2. Mass Balance

Is the West Antarctic Ice Sheet (WAIS) growing or shrinking? In what follows, we briefly review the findings of several researchers who have focused their attention on the mass balance of the WAIS.

Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of radiometrically dated sediment cores collected from the eastern Weddell Sea continental shelf and the western Weddell Sea deep-sea floor in an attempt to better understand the behavior of both the East and West Antarctic ice sheets. In doing so, their data led them to conclude that “significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum,” and that the ice masses that border the Weddell Sea today “are more extensive than they were during the previous glacial minimum.” They concluded “that the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and that the modern West and East Antarctic ice sheets have not yet shrunk to their minimum.” It is thus to be expected—independent of what global air temperature may currently be doing, because of the great inertial forces at work over much longer time scales—that the modern East and West Antarctic Ice Sheets may well continue to shrink and release more icebergs to the Southern Ocean over the coming years, decades and centuries, thereby slowly raising global sea level.

Also studying the combined ice sheets of East and West Antarctica were Wingham *et al.* (1998), who used satellite radar altimeter measurements from 1992 to 1996 to estimate the rate of change of the thickness of nearly two-thirds of the grounded portion of the entire Antarctic Ice Sheet, while using snowfall variability data obtained from ice cores to ultimately calculate the mass balance of the interior of the continental ice sheet over the past century. Their results showed that, at most, the interior of the Antarctic Ice Sheet has been “only a modest source or sink of sea-level mass this century.” As a result, Wingham *et al.* concluded that “a large century-scale imbalance for the Antarctic interior is unlikely,” noting that this conclusion is in harmony with a body of relative sea-level and geodetic evidence “supporting the notion that the grounded ice has been in balance at the millennial scale.” This full set of findings thus suggests that both portions of the Antarctic Ice Sheet may be rather impervious to climate changes of the magnitude characteristic of the Medieval Warm Period and Little Ice Age, which is the type of change most likely to occur—if there is any change at all—in response to the ongoing rise in the air’s CO_2 content.

Davis and Ferguson (2004) evaluated elevation changes of the entire Antarctic ice sheet over the five-year period June 1995 to April 2000, based on more than 123 million elevation change measurements made by the European Space Agency’s European Remote Sensing 2 satellite radar altimeter. They determined the east Antarctic ice sheet had a five-year trend of 1.0 ± 0.6 cm/year, the west Antarctic ice sheet had a five-year trend of -3.6 ± 1.0 cm/year, and the entire Antarctic continent (north of 81.6°S) had a five-year trend of 0.4 ± 0.4 cm/year. In addition, the Pine Island, Thwaites, DeVicq, and Land glaciers of West Antarctica exhibited five-year trends ranging from -26 to—135 cm/year.

In discussing their findings, Davis and Ferguson noted that the strongly negative trends of the coastal glacier outlets "suggest that the basin results are due to dynamic changes in glacier flow," and that recent observations "indicate strong basal melting, caused by ocean temperature increases, is occurring at the grounding lines of these outlet glaciers." They concluded "there is good evidence that the strongly negative trends at these outlet glaciers, the mass balance of the corresponding drainage basins, and the overall mass balance of the west Antarctic ice sheet may be related to increased basal melting caused by ocean temperature increases." Nevertheless, driven by the significantly positive trend of the much larger east Antarctic ice sheet, the ice volume of the entire continent grew ever larger over the last five years of the twentieth century, the majority of which increase, according to Davis and Ferguson, was due to increased snowfall.

One year later, in an "editorial essay" (i.e., not a peer-reviewed submission) published in the journal *Climatic Change*, Oppenheimer and Alley (2005) discussed "the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other," with respect to the WAIS and Greenland Ice Sheet (GIS). After a brief overview of the topic, they noted that "the key questions with respect to both WAIS and GIS are: What processes limit ice velocity, and how much can warming affect those processes?" In answer to these questions, they said that "no consensus has emerged about these issues nor, consequently, about the fate of either ice sheet, a state of affairs reflecting the weakness of current models and uncertainty in paleoclimatic reconstructions."

After a cursory review of the science related to these two key questions, Oppenheimer and Alley say their review "leads to a multitude of questions with respect to the basic science of the ice sheets," which we list below. However, instead of listing them in their original question form, we post them in the form of statements that address what we do not know about the various sub-topics mentioned, which is obviously what prompts the questions in the first place and validates the content of the statements.

(1) We do not know if the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) could occur more generally over the ice sheets.

(2) We do not know if dynamical responses are likely to continue for centuries and propagate further inland or if it is more likely that they will be damped over time.

(3) We do not know if surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.

(4) We do not know if ice sheets made a significant net contribution to sea-level rise over the past several decades.

(5) We do not know what might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.

(6) We do not know the reliability of Antarctic and Southern Ocean temperatures (and polar amplification) that are projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.

(7) We do not know the prospects for expanding measurements and improving models of ice sheets nor the timescales involved.

(8) We do not know if current uncertainties in future ice sheet behavior can be expressed quantitatively.

(9) We do not know what would be useful early warning signs of impending ice sheet disintegration nor when these might be detectable.

(10) We do not know, given current uncertainties, if our present understanding of the vulnerability of either the WAIS or GIS is potentially useful in defining "dangerous anthropogenic interference" with earth's climate system.

(11) We do not know if the concept of a threshold temperature is useful.

(12) We do not know if either ice sheet seems more vulnerable and thus may provide a more immediate measure of climate "danger" and a more pressing target for research.

(13) We do not know if any of the various temperatures proposed in the literature as demarking danger of disintegration for one or the other ice sheet are useful in contributing to a better understanding of "dangerous anthropogenic interference."

(14) We do not know on what timescale future learning might affect the answers to these questions.

Oppenheimer and Alley describe this list of deficiencies in our knowledge of things related to the WAIS as "gaping holes in our understanding" that "will not be closed unless governments provide adequate resources for research." Nevertheless, they claim that "if emissions of the greenhouse gases are not reduced while uncertainties are being resolved, there is a risk of making ice-sheet disintegration nearly inevitable." Obviously, their own analysis contradicts so dire a warning. Given the degree of deficiency in our knowledge of the matter, it is perhaps as likely as not that a continuation of the planet's recovery from the relative cold of the Little Ice Age will lead to a buildup of polar ice.

The following year also saw the publication of another paper that mixed "gaping holes in our understanding" with warnings of dire-sounding WAIS mass losses. Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the 34 months between April 2002 and August 2005. The two researchers concluded that "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea-level rise," all of which mass loss came from the WAIS, since they calculated that the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year.

Velicogna and Wahr admit there is "geophysical contamination ... caused by signals outside Antarctica," including "continental hydrology ... and ocean mass variability." The first of these confounding factors, according to them, "is estimated using monthly, global water storage fields from the Global Land Data Assimilation system," while "the ocean contamination is estimated using a JPL version of the Estimating Circulation and Climate of the Ocean (ECCO) general circulation model."

The two researchers note that the GRACE mass solutions "do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years)."

To adjust for the confounding effect of the variable atmospheric mass above Antarctica, Velicogna and Wahr utilized European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological fields, but they acknowledge that "there are errors in those fields," so they "estimate the secular component of those errors by finding monthly differences between meteorological fields from ECMWF and from the National Centers for Environmental Prediction."

With respect to post-glacial rebound, Velicogna and Wahr say "there are two important sources of error in PGR estimates: the ice history and Earth's viscosity profile." To deal with this problem, they "estimate the PGR contribution and its uncertainties using two ice history models."

All of these estimates and adjustments are convoluted and complex, as well as highly dependent upon various models. Velicogna and Wahr acknowledge that "the PGR contribution is much larger than the uncorrected GRACE trend." In fact, their calculations indicate that the PGR contribution exceeds that of the signal being sought by nearly a factor of five. And they are forced to admit "a significant ice mass trend does not appear until the PGR contribution is removed."

Finally, Velicogna and Wahr's study covered less than a three-year period. Much more likely to be representative of the truth with respect to the WAIS's mass balance are the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent nine-year period to be only 0.08 mm/year compared to the five-times-greater value of 0.4 mm/year calculated by Velicogna and Wahr.

In a contemporaneous study, van de Berg *et al.* (2006) compared results of model-simulated Antarctic surface mass balance (SMB)—which they derived from a regional atmospheric climate model for the time period 1980 to 2004 that used ERA-40 fields as lateral forcings—with "all available SMB observations from Antarctica (N=1900)" in a recalibration process that ultimately allowed them "to construct a best estimate of contemporary Antarctic SMB," where the many real-world observations employed in this process came from the studies of Vaughan *et al.* (1999), van den Broeke *et al.* (1999), Frezzotti *et al.* (2004), Karlof *et al.* (2000), Kaspari *et al.* (2004), Magand *et al.* (2004), Oerter *et al.* (1999, 2000), Smith *et al.* (2002), and Turner *et al.* (2002). Observations were derived by a number of different measurement techniques, including stake arrays, bomb horizons, and chemical analyses of ice cores that covered time periods ranging from a few years to more than a century.

As a result of this effort, van de Berg *et al.* determined that "the SMB integrated over the grounded ice sheet (171 ± 3 mm per year) exceeds previous estimates by as much as 15%," with the largest differences between their results and those of others being "up to one meter per year higher in the coastal zones of East and West Antarctica," concluding that "support or falsification of this result can only be found in new SMB observations from poorly covered high accumulation regions in coastal Antarctica."

In the same year, Wingham *et al*. (2006) "analyzed 1.2 x 10^8 European remote sensing satellite altimeter echoes to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003," which survey, in their words, "covers 85% of the East Antarctic ice sheet and 51% of the West Antarctic ice sheet," which together comprise "72% of the grounded ice sheet." In doing so, they found that "overall, the data, corrected for isostatic rebound, show the ice sheet growing at 5 ± 1 mm per year." To calculate the ice sheet's change in mass, however, "requires knowledge of the density at which the volume changes have occurred," and when the researchers' best estimates of regional differences in this parameter were used, they found that "72% of the Antarctic ice sheet is gaining 27 ± 29 Gt per year, a sink of ocean mass sufficient to *lower* [their italics] global sea levels by 0.08 mm per year." This net *extraction* of water from the global ocean, according to Wingham *et al*., occurs because "mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica."

Ramillien *et al*. (2006) derived new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period July 2002 to March 2005: a loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East Antarctica, which results yielded a net ice loss for the entire continent of 40 km^3/year (which translates to a mean sea-level rise of 0.11 mm/year). This is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea-level rise calculated by Zwally *et al*. (2005), which was derived from elevation changes based on nine years of satellite radar altimetry data obtained from the European Remote-sensing Satellites ERS-1 and -2. Even at that, the GRACE approach is still laden with a host of potential errors, as we noted in our discussion of the Velicogna and Wahr paper, and as both they and Ramillien *et al*. readily admit. In addition, as the latter researchers note in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."

Remy and Frezzotti (2006) reviewed "the results given by three different ways of estimating mass balance, first by measuring the difference between mass input and output, second by monitoring the changing geometry of the continent, and third by modeling both the dynamic and climatic evolution of the continent." In describing their findings, the two researchers state that "the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance." In addition, they report that "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of centuries. However, they note that "later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level."

Van den Broeke *et al*. (2006) employed a regional atmospheric climate model (RACMO2), with snowdrift-related processes calculated offline, to calculate the flux of solid precipitation (Ps), surface sublimation (SU), sublimation from suspended (drifting/saltating) snow particles, horizontal snow drift transport, and surface melt (ME). In doing so, they found that "even without snowdrift-related processes, modeled (Ps-SU-ME) from RACMO2 strongly correlates with 1900 spatially weighted quality-controlled in situ SSMB observations," which result they describe as "remarkable," given that the "model and observations are completely independent." Then, to deal with a remaining systematic elevation bias in the model results, they applied a set of empirical corrections (at 500-m intervals) that "largely eliminated" this final deviation from reality. And after analyzing all of the data-driven results for trends over the period 1980-2004, the four Dutch researchers report that "no trend is found in any of the Antarctic SSMB components, nor in the size of ablation areas."

Krinner *et al*. (2007) used the LMDZ4 atmospheric general circulation model (Hourdin *et al*., 2006) to simulate Antarctic climate for the periods 1981-2000 (to test the model's ability to adequately simulate present conditions) and 2081-2100 (to see what the future might hold for the mass balance of the Antarctic Ice Sheet and its impact on global sea level). This work revealed, first, that "the simulated present-day surface mass balance is skilful on continental scales," which gave them confidence that their results for the end of the twenty-first century would be reasonably accurate as well. Of that latter period a full century from now, they determined that "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds "to a sea-level decrease of 1.2 mm per year by the end of the twenty-first century," which would in turn "lead to a cumulated sea-level decrease of about 6 cm." This result, in their words, occurs because the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation, causing the continent's ice sheet to grow.

The results of this study—based on sea surface boundary conditions taken from IPCC Fourth Assessment Report simulations (Dufresne *et al.*, 2005) that were carried out with the IPSL-CM4 coupled atmosphere-ocean general circulation model (Marti *et al.*, 2005), of which the LMDZ4 model is the atmospheric component—argue strongly against predictions of future catastrophic sea-level rise due to mass wastage of the Antarctic Ice Sheet. In fact, they suggest just the opposite, i.e., that CO_2-induced global warming would tend to buffer the world against such an outcome. That seems to be the message of most of the other major studies of the subject.

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

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4.5.3.3. West Antarctic Ice Sheet and Sea Level

Many of the studies of the West Antarctic Ice Sheet (WAIS) cited in the previous sections of this report address its past and future effects on sea level. In this final section on the WAIS, we bring this body of research together in one place and add other research summaries.

Bindschadler (1998) analyzed the WAIS's historical retreat in terms of its grounding line and ice front. This work revealed that from the time of the Last Glacial Maximum to the present, the retreat of the ice sheet's grounding line had been faster than that of its ice front, which resulted in an expanding Ross Ice Shelf. Although Bindschadler wrote that "the ice front now appears to be nearly stable," there were indications that its grounding line was retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years. Such a retreat was calculated to result in a sustained sea-level rise of 8-13 cm per century. However, even the smallest of these rates-of-rise would require, in Bindschadler's words, "a large negative mass balance for all of West Antarctica," and there were no broad-based data that supported that scenario.

A year later, Reeh (1999) reviewed what was known about the mass balances of both the Greenland and Antarctic ice sheets, concluding that the future contribution of the Greenland and Antarctic ice sheets to global sea level depends upon their past climate and dynamic histories as much as it does upon future climate. With respect to potential climate change, Reeh determined there was a broad consensus that the effect of a 1°C climatic warming on the Antarctic ice sheet would be a *fall* in global sea level on the order of 0.2 to 0.7 millimeters per year.

The following year, Cuffey and Marshall (2000) reevaluated previous model estimates of the Greenland ice sheet's contribution to sea-level rise during the last interglacial, based on a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. Their results suggested that the Greenland ice sheet was much smaller during the last interglacial than previously thought, with melting of the ice sheet contributing somewhere between four and five-and-a-half meters to sea-level rise. According to Hvidberg (2000), this finding suggests that "high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change."

Oppenheimer and Alley (2005) discussed "the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other," with respect to both the West Antarctic and Greenland Ice Sheets. Their review of the subject led them to conclude that we simply do not know if these ice sheets had made a significant contribution to sea-level rise over the past several decades.

One year later, however, the world was exposed to a different view of the issue when Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the 34 months between April 2002 and August 2005. The two researchers concluded that "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea-level rise," all of which mass loss came from the WAIS, since they calculated that the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year.

The many estimates and adjustments used by Velicogna and Wahr to reach this conclusion were described in Section 4.5.3.2. For example, the adjustment for post-glacial rebound alone exceeded the signal being sought by nearly a factor of five. Moreover, the study covers less than a three-year period, which compares poorly with the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent nine-year period to be only 0.08 mm/year.

Ramillien *et al.* (2006) also used GRACE data to derive estimates of the mass balances of the East and West Antarctic ice sheets for the period July 2002 to March 2005, obtaining a loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East Antarctica, which results yielded a net ice loss for the entire continent of only 40 km^3/year (which translates to a mean sea-level rise of 0.11 mm/year), as opposed to the 152 km^3/year ice loss calculated by Velicogna and Wahr (which translates to a nearly four times larger mean sea-level rise of 0.40 mm/year). Ramillien *et al.* note in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations." That caveat also applies to the Velicogna and Wahr analysis.

About the same time, Wingham *et al.* (2006) analyzed European remote sensing satellite altimeter echoes to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. They found that "72% of the Antarctic ice sheet is gaining 27 ± 29 Gt per year, a sink of ocean mass sufficient to *lower* [their italics] global sea levels by 0.08 mm per year." This net extraction of water from the global ocean, according to Wingham *et al.*, occurs because "mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica."

Remy and Frezzotti (2006) reviewed "the results given by three different ways of estimating mass balance, first by measuring the difference between mass input and output, second by monitoring the changing geometry of the continent, and third by modeling both the dynamic and climatic evolution of the continent." They report that "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of *centuries*. However, they note that "later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level."

Krinner *et al.* (2007), in a study summarized in Section 5.6.3.3., used the LMDZ4 atmospheric general circulation model of Hourdin *et al.* (2006) to simulate Antarctic climate for the periods 1981-2000 (to test the model's ability to adequately simulate present conditions) and 2081-2100 (to see what the future might hold for the mass balance of the Antarctic Ice Sheet and its impact on global sea level). They determined that "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds "to a sea-level decrease of 1.2 mm per year by the end of the twenty-first century," which would in turn "lead to a cumulated sea-level decrease of about 6 cm." This result occurs because the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation, causing the continent's ice sheet to grow.

There has been very little change in global sea level due to wastage of the WAIS over the past few decades, and there will probably be little change in both the near and far future. What wastage might occur along the coastal area of the ice sheet over the long term would likely be countered, or more than countered, by greater inland snowfall. In the case of the latter possibility, the entire Antarctic Ice Sheet could well compensate for any long-term wastage of the Greenland Ice Sheet that might occur.

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

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4.5.4. Greenland Ice Cap

Studies of the growth and decay of polar ice sheets are of great importance because of the relationships of these phenomena to global warming and the impacts they can have on sea level. In this section, we review a number of such studies that pertain to the Greenland Ice Sheet.

In the March 24, 2006 issue of *Science*, several commentaries heralded accelerating discharges of glacial ice from Greenland and Antarctica, while dispensing dire warnings of an imminent large, rapid, and accelerating sea-level rise (Bindschadler, 2006; Joughin, 2006; Kerr, 2006; Kennedy and Hanson, 2006). This distressing news was based largely on three reports published in the same issue (Ekstrom *et al*., 2006; Otto-Bliesner *et al*., 2006; Overpeck *et al*., 2006), wherein the unnerving phenomena were attributed to anthropogenic-induced global warming.

Consider the report of Ekstrom *et al*., who studied "glacial earthquakes" caused by sudden sliding motions of glaciers on Greenland. Over the period from January 1993 to October 2005, they determined that (1) *all* of the best-recorded quakes were associated with major outlet glaciers on the east and west coasts of Greenland between approximately 65 and 76°N latitude, (2) “a clear increase in the number of events is seen starting in 2002,” and (3) “to date in 2005, twice as many events have been detected as in any year before 2002.”

With respect to the reason for the recent increase in glacial activity on Greenland, Clayton Sandell of ABC News on March 23, 2006 quoted Ekstrom as saying “I think it is very hard not to associate this with global warming,” which sentiment appears to be shared by almost all of the authors of the seven *Science* articles. Unwilling to join that conclusion, however, was Joughin, who in the very same issue presented histories of summer temperature at four coastal Greenland stations located within the same latitude range as the sites of the glacial earthquakes, which histories suggest that it was warmer in this region back in the 1930s than it was over the period of Ekstrom *et al.*’s analysis.

Based on these data, Joughin concluded that the recent warming in Greenland “is too short to determine whether it is an anthropogenic effect or natural variability,” a position that is supported by many scientists cited previously in this chapter, and more in the discussion that follows.

A study based on mean monthly temperatures of 37 Arctic and seven sub-Arctic stations and temperature anomalies of 30 grid-boxes from the updated dataset of Jones by Przybylak (2000) found (1) “in the Arctic, the highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s,” (2) “even in the 1950s the temperature was higher than in the last 10 years,” (3) “since the mid-1970s, the annual temperature shows no clear trend,” and (4) “the level of temperature in Greenland in the last 10-20 years is similar to that observed in the 19th century.” These findings led him to conclude that the meteorological record “shows that the observed variations in air temperature in the real Arctic are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect,” because, in his words, “the temperature predictions produced by numerical climate models significantly differ from those actually observed.”

In light of these several other studies of real-world observations, it is clear that the recent upswing in glacial activity on Greenland likely has had nothing to do with anthropogenic-induced global warming, as temperatures there have yet to rise either as fast or as high as they did during the great warming of the 1920s, which was clearly a natural phenomenon. It is also important to recognize the fact that coastal glacial discharge represents only half of the equation relating to sea-level change, the other half being inland ice accumulation derived from precipitation; and when the mass balance of the entire Greenland ice sheet was recently assessed via satellite radar altimetry, quite a different result was obtained than that suggested by the seven *Science* papers.

Zwally *et al.* (2005) found that although “the Greenland ice sheet is thinning at the margins,” it is “growing inland with a small overall mass gain.” In fact, for the 11-year period 1992-2003, Johannessen *et al.* (2005) found that “below 1500 meters, the elevation-change rate is [a negative] 2.0 ± 0.9 cm/year, in qualitative agreement with reported thinning in the ice-sheet margins,” but that “an increase of 6.4 ± 0.2 cm/year is found in the vast interior areas above 1500 meters.” Spatially averaged over the bulk of the ice sheet, the net result, according to the latter researchers, was a mean increase of 5.4 ± 0.2 cm/year, “or ~60 cm over 11 years, or ~54 cm when corrected for isostatic uplift.” Consequently, the Greenland Ice Sheet would appear to have experienced no net loss of mass over the last decade for which data are available. To the contrary, it was likely host to a net accumulation of ice, which Zwally *et al.* found to be producing a 0.03 ± 0.01 mm/year decline in sea-level.

In an attempt to downplay the significance of these inconvenient findings, Kerr quoted Zwally as saying he believes that “right now” the Greenland Ice Sheet is experiencing a net loss of mass. Why? Kerr says Zwally’s belief is “based on his gut feeling about the most recent radar and laser observations.” Gut feelings are a poor substitute for comprehensive real-world measurements, and even if Zwally’s intestines are ultimately found to be correct, their confirmation would only demonstrate just how rapidly the Greenland environment can change. We would have to wait and see how long the mass losses prevailed in order to assess their significance within the context of the CO_2-induced global warming debate. For the present and immediate future, therefore, we have no choice but to stick with what existent data and analyses suggest; i.e., that cumulatively since the early 1990s and conservatively (since the balance is likely still positive), there has been no net loss of mass from the Greenland Ice Sheet.

The recent study by Eldrett *et al.* (2007) provides further evidence that the IPCC’s view of melting sea ice is wrong. The five researchers from the School of

Ocean and Earth Science of the National Oceanography Centre of the University of Southampton in the UK report they "have generated a new stratigraphy for three key Deep Sea Drilling Project/Ocean Drilling Program sites by calibrating dinocyst events to the geomagnetic polarity timescale." In doing so, they say their detailed core observations revealed evidence for "extensive ice-rafted debris, including macroscopic dropstones, in late Eocene to early Oligocene sediments from the Norwegian-Greenland Sea that were deposited between about 38 and 30 million years ago." They further report that their data "indicate sediment rafting by glacial ice, rather than sea ice, and point to East Greenland as the likely source," and they conclude that their data thus suggest "the existence of (at least) isolated glaciers on Greenland about 20 million years earlier than previously documented."

What is particularly interesting about this finding, as Eldrett *et al*. describe it, is that it indicates the presence of glacial ice on Greenland "at a time when temperatures and atmospheric carbon dioxide concentrations were substantially higher." How much higher? According to graphs the researchers present, ocean bottom-water temperatures were 5-8°C warmer, while atmospheric CO_2 concentrations were as much as four times greater than they are today.

The problem these observations provide for those who hold to the view that global warming will melt the Greenland Ice Sheet, to quote Eldrett *et al*., is that "palaeoclimate model experiments generate substantial ice sheets in the Northern Hemisphere for the Eocene only in runs where carbon dioxide levels are lower (approaching the pre-anthropogenic level) than suggested by proxy records," which records indicate atmospheric CO_2 concentrations fully two to seven times greater than the pre-anthropogenic level during the time of the newly detected ice sheets.

"Regardless," as the researchers say, their data "provide the first stratigraphically extensive evidence for the existence of continental ice in the Northern Hemisphere during the Palaeogene," which "is about 20 million years earlier than previously documented, at a time when global deep water temperatures and, by extension, surface water temperatures at high latitude, were much warmer." Therefore—and also "by extension"—we now have evidence of a much warmer period of time that failed to melt the Greenland Ice Sheet.

Continuing, Krabill *et al*. (2000) used data obtained from aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999, together with previously reported data from southern Greenland, to evaluate the mass balance of the Greenland Ice Sheet. Above an elevation of 2,000 meters they found areas of both thinning and thickening; and these phenomena nearly balanced each other, so that in the south there was a net thinning of 11 ± 7 mm/year, while in the north there was a net thickening of 14 ± 7 mm/year. Altogether, the entire region exhibited a net thickening of 5 ± 5 mm/year; but in correcting for bedrock uplift, which averaged 4 mm/year in the south and 5 mm/year in the north, the average thickening rate decreased to practically nothing. The word used by Krabill *et al*. to describe the net balance was "zero."

At lower elevations, thinning was found to predominate along approximately 70 percent of the coast. Here, however, flight lines were few and far between; so few and far between, in fact, that the researchers said that "in order to extend our estimates to the edge of the ice sheet in areas not bounded by our surveys, we calculated a hypothetical thinning rate on the basis of the coastal positive degree day anomalies." Then, they interpolated between this calculated coastal thinning rate and the nearest observed elevation changes to obtain their final answer: a total net reduction in ice volume of 51 km^3/year.

Unfortunately, it is difficult to know what estimates derived from interpolations based on calculations of a hypothetical thinning rate mean. We question their significance; and the researchers themselves do the same. They note that they do not have a "satisfactory explanation" for the "widespread thinning at elevations below 2000 m," which suggests that the reason this phenomenon is unexplainable is that it may not be real. The authors further note that even if the thinning was real, it could not be due to global or regional warming, since Greenland temperature records indicate "the 1980s and early 1990s were about half a degree cooler than the 96-year mean."

After discussing some other factors that could be involved, Krabill *et al*. state they are left with changes in ice dynamics as the most likely cause of the hypothetical ice sheet thinning. But they admit in their final sentence that "we have no evidence for such changes, and we cannot explain why they should apply to many glaciers in different parts of Greenland." It would seem logical to admit this study resolves almost nothing about the mass balance of the coastal regions of the Greenland Ice Sheet and nothing about the subject of global warming and its effect or non-effect upon this hypothetical phenomenon.

In a preliminary step required to better understand the relationship of glacier dynamics to climate change in West Greenland, Taurisano *et al*. (2004) described the temperature trends of the Nuuk fjord area during the past century. This analysis of all pertinent regional data led them to conclude that "at all stations in the Nuuk fjord, both the annual mean and the average temperature of the three summer months (June, July and August) exhibit a pattern in agreement with the trends observed at other stations in south and west Greenland (Humlum 1999; Hanna and Cappelen, 2003)." As they describe it, the temperature data "show that a warming trend occurred in the Nuuk fjord during the first 50 years of the 1900s, followed by a cooling over the second part of the century, when the average annual temperatures decreased by approximately 1.5°C." Coincident with this cooling trend there was also what they describe as "a remarkable increase in the number of snowfall days (+59 days)." What is more, they report that "not only did the cooling affect the winter months, as suggested by Hannna and Cappelen (2002), but also the summer mean," noting that "the summer cooling is rather important information for glaciological studies, due to the ablation-temperature relations." Finally, they report there was no significant trend in annual precipitation. In their concluding discussion, Taurisano *et al*. remark that the temperature data they studied "reveal a pattern which is common to most other stations in Greenland."

Rignot and Kanagaratnam (2005) used satellite radar interferometry observations of Greenland to detect what they described as "widespread glacier acceleration." Calculating that this phenomenon had led to a doubling of the ice sheet mass deficit in the past decade and, therefore, a comparable increase in Greenland's contribution to rising sea levels, they went on to claim that "as more glaciers accelerate ... the contribution of Greenland to sea-level rise will continue to increase."

With respect to these contentions, we have no problem with what the two researchers have observed with respect to Greenland's glaciers; but we feel compelled to note that what they have calculated with respect to the mass balance of Greenland's Ice Sheet and what they say it implies about sea level are contradicted by more inclusive real-world data. One reason for this discrepancy is that instead of relying on measurements for this evaluation, Rignot and Kanagaratnam relied on the calculations of Hanna *et al*. (2005), who used meteorological models "to retrieve annual accumulation, runoff, and surface mass balance." When actual measurements of the ice sheet via satellite radar altimetry are employed, a decidedly different perspective is obtained, as indicated by the work of Zwally *et al*. (2005) and Johannessen *et al*. (2005), which we cited earlier. Consequently, and contrary to the claim of Rignot and Kanagaratnam, Greenland would appear to have experienced no ice sheet mass deficit in the past decade.

Shepherd and Wingham (2007) reviewed what is known about sea-level contributions arising from wastage of the Antarctic and Greenland Ice Sheets, concentrating on the results of 14 satellite-based estimates of the imbalances of the polar ice sheets that have been derived since 1998. These studies have been of three major types—standard mass budget analyses, altimetry measurements of ice-sheet volume changes, and measurements of the ice sheets' changing gravitational attraction—and they have yielded a diversity of values, ranging from a sea-level-rise-equivalent of 1.0 mm/year to a sea-level-fall-equivalent of 0.15 mm/year. The two researchers conclude that the current "best estimate" of the contribution of polar ice wastage (from both Greenland and Antarctica) to global sea-level change is a rise of 0.35 millimeters per year, which over a century amounts to only 35 millimeters.

Even this unimpressive sea-level increase may be too large an estimate, for although two of Greenland's largest outlet glaciers doubled their rates of mass loss in less than a year in 2004—causing the IPCC to claim the Greenland Ice Sheet was responding much more rapidly to global warming than anyone had ever expected—Howat *et al*. (2007) report that the two glaciers' rates of mass loss "decreased in 2006 to near the previous rates." And these observations, in their words, "suggest that special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends."

In conclusion, the part of the Northern Hemisphere that holds the lion's share of the hemisphere's ice has been cooling for the past half-century, and at a very significant rate, making it unlikely that its frozen water will be released to the world's oceans. In addition, because the annual number of snowfall days over much of Greenland has increased so dramatically over the same time period, it is possible that enhanced accumulation of snow on its huge ice sheet may be compensating for the melting of many of the world's mountain glaciers and keeping global sea level in check for this reason too. Lastly, Greenland's temperature trend of the past half-century has been just the opposite—and strikingly so—of that which is claimed for the Northern Hemisphere and the world by 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/s/sealevelgreenland.php.

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