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Observations: The Cryosphere

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Key Findings

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice in glaciers, icecaps, and sea ice. Worries about untoward melting of the cryosphere in response to carbon dioxide-forced temperature rise have existed since the earliest days of global warming alarm in the 1980s.

- Satellite and airborne geophysical datasets used to quantify the global ice budget are short and the methods involved in their infancy, but results to date suggest both the Greenland and Antarctic Ice Caps are close to balance.

- Deep ice cores from Antarctica and Greenland show climate change occurs as both major glacial-interglacial cycles and as shorter decadal and centennial events with high rates of warming and cooling, including abrupt temperature steps.
- Observed changes in temperature, snowfall, ice flow speed, glacial extent, and iceberg calving in both Greenland and Antarctica appear to lie within the limits of natural climate variation.
- Global sea-ice cover remains similar in area to that at the start of satellite observations in 1979, with ice shrinkage in the Arctic Ocean since then being offset by growth around Antarctica.

- During the past 25,000 years (late Pleistocene and Holocene) glaciers around the world have fluctuated broadly in concert with changing climate, at times shrinking to positions and volumes smaller than today.
- This fact notwithstanding, mountain glaciers around the world show a wide variety of responses to local climate variation, and do not respond to global temperature change in a simple, uniform way.
- Tropical mountain glaciers in both South America and Africa have retreated in the past 100 years because of reduced precipitation and increased solar radiation; some glaciers elsewhere also have retreated since the end of the Little Ice Age.
- The data on global glacial history and ice mass balance do not support the claims made by the IPCC that CO₂ emissions are causing most glaciers today to retreat and melt.
- No evidence exists that current changes in Arctic permafrost are other than natural or that methane released by thawing would significantly affect Earth's climate.
- Most of Earth's gas hydrates occur at low saturations and in sediments at such great depths below the seafloor or onshore permafrost that they will barely be affected by warming over even one thousand years.

Introduction

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice. The cryosphere forms the frozen part of the larger hydrosphere, which encompasses all the water contained in rain, rivers, lakes, and oceans. The processes and characteristics of the cryosphere and hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, the hydrosphere and cryosphere also change in response to external climate change forcings, some of which may be natural (e.g., changed solar insolation) and some of human origin (e.g., industrial greenhouse gas forcing). This distinction, which applies to all aspects of Earth's climate system, is easy to draw in principle, but in practice it has

proved difficult to establish that any specific changes in the cryosphere or hydrosphere documented over the past century have their origins in human activity.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC) commented, "recent decreases in ice mass are correlated with rising surface air temperatures. This is especially true in the region north of 65°N, where temperatures have increased by about twice the global average from 1965 to 2005" (IPCC 2007, p. 339). The IPCC went on to report decreased snow cover "in most regions, especially in spring and summer," freeze-up dates in the Northern Hemisphere occurring later, breakup dates occurring earlier, declines in sea-ice extent, and similar findings. All of these statements were made against the background assumption that the warming was of anthropogenic origin.

The authors of the 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC) and its 2011 interim report contended many of the IPCC's findings on this subject were incorrect, resulting from the inappropriate use of circumstantial evidence, cherry-picking of data, or misrepresentation of available research. Specifically, Idso and Singer (2009, p. 4) reported:

Glaciers around the world are continuously advancing and retreating, with a general pattern of retreat since the end of the Little Ice Age. There is no evidence of an increased rate of melting overall since CO₂ levels rose above their pre-industrial levels, suggesting CO₂ is not responsible for glaciers melting.

Sea ice area and extent have continued to increase around Antarctica over the past few decades. Evidence shows that much of the reported thinning of Arctic sea ice that occurred in the 1990s 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 the decades to come, totally irrespective of past or future changes in the air's CO₂ content. The Arctic appears to have recovered from its 2007 decline.

By themselves such facts as melting glaciers and Arctic sea ice, while interesting, tell one nothing about causation. Any significant warming, whether anthropogenic or natural, will melt ice. To claim anthropogenic global warming (AGW) is occurring based on such information is to confuse the consequences of warming with its cause, constituting

an error in logic. Similar arguments apply also to fluctuations in glacier mass, sea ice, precipitation, and sea level, all of which can be forced by many factors other than temperature change. It is entirely inappropriate to use this type of circumstantial evidence to claim allegedly dangerous human-caused warming is occurring.

This chapter builds on the earlier NIPCC conclusions, bringing up to date our summary of the extensive scientific literature on global warming as it might affect the cryosphere. We again find changes in glacier and sea-ice extent frequently occur in ways that contradict, and rarely reinforce, the claims of the IPCC and the projections of its climate models. Overall, new research conducted since 2007 reinforces NIPCC's 2009 interim summary and finds less melting of ice in the Arctic, Antarctic, and mountain glaciers than previously feared, and no melting at all that could be uniquely attributed to rising carbon dioxide levels.

Some of the key concepts of cryospheric science that are relevant to the climate change issue are presented in the remainder of this introduction to set the stage for the analysis that follows.

GLACIER MASS BALANCE

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation (snowfall) dominates in winter, ablation (melting, avalanching, calving) in summer. If the two are equal, the net mass balance of a glacier or icecap is zero and its snout or periphery will remain stable; otherwise, a glacier will grow in size (advance) if accumulation is the greater (positive mass balance) or shrink and retreat if ablation is the greater (negative mass balance). In this way, climatic factors control glacial behavior, changes in which can be used as indicators of changing climatic conditions over time.

MEASUREMENTS OF MODERN MASS BALANCE

Little data exists with which to accurately quantify glacial mass balance prior to the twenty-first century. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment); and ICESat (Ice Cloud and Land Elevation Satellite)—are in their infancy and often of doubtful accuracy, not least because of the complexity of the data processing needed to correct and interpret the data sets. Also, the data sets are so short they

inevitably fail to capture the full range of climatic multidecadal variability.

Correction of satellite data requires an accurate model of the shape of Earth as represented by a spheroidal Terrestrial Reference Frame (TRF). The inadequacy of current TRFs is acknowledged by the Jet Propulsion Laboratory (NASA), which plans to launch a Geodetic Reference Antenna in Space (GRASP) satellite in order to establish a more accurate TRF. Until the accuracy of the TRF has been improved in this or other ways, spaceborne geophysical studies of ice-sheet mass balance and sea-level change will remain uncertain.

ICE CORES

The ice sheets of Greenland and Antarctica contain a remarkable layered ice record of past climatic change back to 120,000 and almost 1 million years ago, respectively. Changing oxygen isotope ratios in the ice act as a proxy for ancient air temperature change; analysis of trapped gases allows the estimation of the CO₂ and CH₄ content of the former atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric physico-chemical parameters also can be determined.

The ice cores show the climate record is permeated by both gradual and rapid change. This includes not only the major glacial-interglacial cycles, but also abrupt climate swings with high short-term rates of warming and cooling. Pleistocene and Holocene fluctuations in glacial activity onland match the climatic events represented in ice cores (and correlative deep sea mud cores), establishing the fidelity of core data as a record of past climatic change.

A particularly important result from ice core studies is the observation that changes in ancient CO₂ lag the equivalent changes in temperature by up to a thousand years, so CO₂ increase cannot be the cause of the warmings documented in the cores.

RECENT HISTORIC EVIDENCE

Glaciers have advanced and retreated during alternating warm and cool climatic periods throughout geological history. Since the mid-nineteenth century, the overall trend is that glaciers have lost mass as the Earth warmed after the Little Ice Age (LIA). No “unprecedented warming” has occurred during the twentieth century. Many glaciers retreated strongly during the 1915–1945 warm period before major industrial CO₂ emissions, advancing again during the 1945–1977 cool period when CO₂ emissions were soaring. This is precisely the opposite of what would

have happened if human-related CO₂ emissions caused enhanced warming and melting.

ANTARCTICA

Antarctica covers 14 million km² in area, is 98 percent covered by glacial ice that averages 2.4 km in thickness, corresponds to 90 percent of the world's ice, and represents about 70 percent of the world's fresh water. Melting all Antarctic ice would raise sea level by about 72 m. The average daily temperatures at the South Pole and Vostock, respectively, are -49.4° C and -55.1° C. In order to melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0° C. This is not happening now, nor is it likely to happen soon. The main (east) Antarctic ice sheet has been cooling since 1957 and ice accumulation is increasing rather than decreasing. For the same period, since 1957, warming and ice melting have occurred along the West Antarctic Peninsula, which represents 13 percent of Antarctic Ice. This melting may have an oceanographic rather than a meteorological cause.

So far as we are able to measure it accurately, the Antarctic ice mass is effectively stable on the short historic (meteorological) time scale. On the longer-term climatic scale, Antarctic and nearby ice volume has fluctuated in parallel with millennial-scale climate variability, including ice shrinkage during the Medieval Warm Period to positions that have not been attained again today.

Three facts confirm the likely modern stability of the East Antarctic Ice Sheet: (1) the late twentieth century global warming expected to melt the icecap lay well within the bounds of natural variation and has now ceased; (2) were warming to resume, the probable regional response would be enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; and (3) despite the past few interglacials being up to 5° C warmer than was the Holocene, sediment cores adjacent to Antarctica provide no evidence for any dramatic breakups of the WAIS over the past few glacial cycles.

GREENLAND

The Greenland ice sheet is the second largest ice mass in the world, being 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km². The mean altitude of the ice surface is 2,135 m and the ice is nearly 3 km thick in central Greenland. Nonetheless, this represents only a small part (8 percent) of global ice volume and 7 m of sea-level equivalent. During the last glaciation 20,000 years ago, the Greenland

massif was part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Although temperatures in Greenland rose during the late twentieth century, they did not rise as fast or as high as they did during the previous natural warming in the 1920s–1930s. Further-more, the temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years, indicating recent warmth is not unprecedented and not necessarily caused by rising CO₂.

The Little Ice Age in Greenland lasted to 1918, helping to achieve a subsequent rate of warming there for 1918–1935 that was 70 percent greater than the rate of warming for 1978–2004. The mean rate-of-rise in atmospheric CO₂ during this period was almost five times greater during the more recent warming.

Recent satellite-borne geophysical measurements suggest Greenland, like Antarctica, is in a state of approximate mass balance, quite contrary to the alarmist tone of much public commentary. Modern changes in glacier activity or volume in Greenland have no necessary or likely relationship with anthropogenic global warming and are more probably natural.

OTHER ARCTIC GLACIERS

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO₂-induced global warming.

Abundant field evidence shows high Arctic glaciers did not uniformly waste away during the late twentieth century and changed precipitation was as common a cause of glacial change as was changed temperature. As some glaciers advanced, others retreated; in addition, a Jan Mayen Glacier advance was accompanied by warming rather than cooling.

To the degree glaciers present in particular regions have retreated over the past 150 years (e.g., the Canadian Arctic), this is no more than would be expected for glaciers emerging from the Little Ice Age and does not require CO₂ emissions as an additional explanation.

MOUNTAIN GLACIERS

Montane ice is a volumetrically trivial part of the cryosphere (0.6 percent) and represents just 45 cm of sea-level equivalent. Nonetheless, changes in mountain glaciers are important in human terms because the well-watered alpine meadows that occur down-valley from glacier termini have long attracted settlers, and because rivers emanating from glacial valleys are an important wider water resource.

Few quantitative observations of mountain glaciers exist prior to 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Over the past millennium, glaciers have advanced and retreated multiple times as Earth passed successively through the Medieval Warm Period, Little Ice Age, and twentieth century warming. For many of the glaciers that show twentieth century retreat, shrinkage generally started in the late nineteenth century, many decades before human-related CO₂ emissions could have been a factor.

Research on mountain glaciers worldwide has failed to provide evidence for unnatural glacial retreat in the late twentieth century forced by human carbon dioxide emissions. Instead, historic glacial change correlates with the de Vries (~208 year) and Gleissberg (~80 year) solar cycles or fluctuates in sympathy with multidecadal oscillations like the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO).

TROPICAL GLACIERS

African mountain glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights. Repeated allegations have been made that the icecap on Kenya's iconic Mt. Kilimanjaro is melting away because of human-caused global warming.

Similar glacier retreat has been occurring throughout the tropics since the late nineteenth century, including on Mts. Kilimanjaro, Kenya, and Rwenzori in Africa and glaciers in Peru and Bolivia. Studies show reduced precipitation and increased solar radiation (due to decreasing cloudiness) have been the dominant factors influencing ice wastage, which commenced long before human-related CO₂ emissions could have been the cause. Despite common assertions, warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

ARCTIC SEA ICE

It is often claimed that CO₂-induced global warming is melting sea ice, especially in the Arctic Ocean. Semi-permanent oceanic sea ice exists today near the North Pole, but fringing sea ice is an annual, seasonal feature in both the Arctic and around Antarctica. Such ice is susceptible to fast advance or retreat, depending

upon local oceanographic and atmospheric conditions. Major sea-ice changes are not uncommon and not necessarily a result of temperature change; often, pulses of warm ocean water or atypical wind motions play a greater role.

Historical records demonstrate Arctic sea ice has fluctuated in sympathy with past multidecadal cycles in temperature, including shrinking to an area similar to that of the 2007 minimum during periods of relative warmth in the 1780s and 1940s; the pattern is that of the well-known multidecadal climate rhythms such as the Atlantic Oscillation and the Arctic and Arctic Ocean Oscillations. Earlier still, about 8,000 years ago during the Holocene Climatic Optimum, temperatures up to 2.5° C warmer than today resulted in what was probably an almost ice-free Arctic Ocean.

Arctic sea-ice cover varies dramatically and naturally over quite short periods of time, and Arctic fauna and flora, including the iconic polar bear, are adapted to deal with the environmental exigencies that result. It has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or a human economic perspective. No convincing research study demonstrates the level of sea-ice in the Arctic Ocean stood at some "ideal" level prior to the Industrial Revolution.

ANTARCTIC SEA ICE

Satellite-mounted sensors document a growth in both pack ice and fast ice across the East Antarctic region since 1979. Between 1979 and 2008, sea ice increased in area by about half a million square kilometers: a 2–3 percent increase during winter and spring and a 5–7 percent increase during summer. Thus the recent trend toward decreasing sea ice in the Arctic since 1979 has been counterbalanced by increasing sea ice in Antarctica, for a net result of little overall change in global sea-ice area.

This result is not consistent with the climate models that project high latitude warming and decreases in polar sea-ice in both hemispheres.

LATE PLEISTOCENE AND HOLOCENE CHANGE

Geological studies establish that before and during the last deglaciation (between 15,000 and 11,500 years ago), multiple, intense, and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. An intrinsic variability of about 1,500 years, termed the Dansgaard-Oeschger rhythm,

exhibits a magnitude and intensity up to 20 times greater than warming over the past century.

Similar climatic rhythms continued over the Holocene (last 11,700 years), as seen in the record from Greenland ice cores. The four most important characteristics of the documented variability are: the presence of a temperature peak about 2.5° C warmer than today at ~8,000 y BP; a general cooling trend thereafter; the punctuation of the record by 1,500-year-long, alternating rhythms of warmer and colder climate (termed Bond Cycles, and probably of solar origin), the warm peaks of which exceeded late twentieth century warmth; and for more than 90 percent of the past 10,000 years temperature has been 1–3°C warmer than today.

THE CRYOSPHERE THROUGH DEEP TIME

The total amount of ice in the cryosphere varies from time to time in sympathy with Earth's always-changing climate. Sixty million years ago, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in both the Antarctic and Greenland began after 45 million years ago, although it was probably only about 10 million years ago that a major northern icecap started to accumulate. Global cooling from 3 million years ago onward resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene ice ages.

Throughout this process of high-latitude ice-cap growth, the precise location and size of ice masses worldwide depended upon the vicissitudes of both local and global climate. Never, for any significant period of time, was a stable, global "ice mass balance" attained. Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will again vary in sympathy.

There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation, Nor is there any scientific basis for the common, implicit assumption that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

CONTEXT FOR THE MODERN CRYOSPHERE

The geological record of past climate provides an essential context largely missing from discussions about modern ice-volume changes and their significance. The rate and magnitude of twentieth century warming were small compared to the

magnitude of the profound natural climate reversals that have occurred over the past 20,000 years. Most importantly, too, none of the documented late Pleistocene and Holocene climatic events was accompanied by significant parallel change in atmospheric levels of carbon dioxide. Furthermore, the rate of glacier retreat has not increased over the period of large increases in CO₂ emissions over the past 60 years.

The data on global glacial history and ice mass balance simply do not support the claims made by the IPCC that CO₂ emissions are causing most glaciers today to retreat and melt. Instead, the null hypothesis—that twentieth century warming reflected natural climatic variation—remains valid.

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5.1 Glacial Dynamics

Glaciers are masses of granular snow and ice formed by compaction and recrystallization of snowfall, lying largely or wholly on land and showing evidence of past or present movement. The transformation of snow into ice in thicknesses great enough to promote motion on land is important. In addition to low temperatures, precipitation is needed for glaciers to develop. Some polar areas have no glaciers because even though the climate is cold, little snowfall occurs and the conditions needed to convert snow into ice occur infrequently.

Because the formation and persistence of glaciers are directly linked to climate, their deposits and landforms provide evidence for interpretation of past climatic changes. Thus an understanding of glacial processes is important for the study of ancient climates.

Although ice is solid at atmospheric pressure, it has low shear strength and will readily deform

plastically under shear stresses beyond 1 kg/cm^2 , resulting in continuous plastic flow.

$$\varepsilon \text{ (strain)} = k[\rho(\text{ice density}) g \text{ (gravity)} t \text{ (ice thickness)} \sin \alpha \text{ (slope of ice surface)}]^n$$

The constant (k) increases with temperature, as does the n^{th} power in this equation. Thus, plastic flow in ice is very sensitive to temperature—the warmer the ice, the more easily it deforms. Strain rates at 0°C may be 10 times greater than at -22°C . Temperate glaciers, which are near the pressure-melting point of ice, generally exhibit higher rates of plastic flow than do polar glaciers, whose temperature is well below the freezing point. As seen in the equation above, not only temperature but also ice thickness and the slope of the ice surface affect flow velocity. The thicker the ice, the faster it flows, and the steeper the ice surface, the faster it flows.

In addition to plastic flow, glaciers also move by sliding over their bed. Basal sliding of glaciers increases where subglacial meltwater is present, especially if the subglacial water is under hydrostatic pressure, which then reduces the effective weight of the overlying ice and diminishes friction. Basal sliding is thus greatest in temperate glaciers and may be absent in polar glaciers, which are frozen to their base.

In general glaciers grow, flow, and melt continuously, within the context of an overall annual mass budget of gains and losses that is not necessarily balanced over time. Snow falls on high ground, compacts, and becomes solid ice. More precipitation of snow forms another layer on the top, so the ice grows thicker by the addition of new layers at the surface. When the ice is thick enough it starts to flow plastically under the force of gravity.

The mechanism of glacier flow needs to be considered carefully. Ice does not simply slide on its base. Nonetheless, sliding is a significant contributor of downslope movement for some glaciers, varying between 0 percent for the Meserve Glacier (Antarctica) and 75 percent for the Athabaska Glacier (Canada) (Paterson, 1981; Holdsworth and Bull, 1970).

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5.1.1 Plastic Flow

When stress in ice exceeds its elastic limit, ice becomes plastic; this allows limitless permanent deformation to occur, because the ice flows continuously under its own weight. Ice flows plastically by three mechanisms, namely:

- intergranular shifting,
- intragranular shifting, and
- recrystallization.

In intergranular shifting, differential movement takes place between ice grains by rotation and sliding between individual ice crystals. For intragranular shifting, movement occurs by gliding along basal planes within ice crystals; this is a significant mechanism of glacial flow, easy slippage occurring along planes parallel to the base of the crystals, where fewer atomic bonds need to be broken for translation to occur. Recrystallization of ice facilitates down-glacier transfer of material by creep. Pressure at grain boundaries can melt ice at the pressure melting temperature, and meltwater can then migrate to sites of lower pressure (in the down ice direction), where it refreezes. The net effect of these three processes is plastic flow of the ice.

Three factors determine the magnitude of plastic flow in ice, namely:

- creep is proportional to temperature;
- creep is proportional to ice thickness (i.e., to the stress produced by the weight of overlying ice); and
- creep is proportional to the slope of the ice surface.

The closer the temperature comes to the melting point, the greater is the creep rate. The creep rate at -1°C is about 1,000 times greater than at -20°C .

The stress law of creep means the thicker the ice, the faster the flow. In valley glaciers the upper 30 m of the glacier cannot flow, because the ice is brittle and cracks to form crevasses in the rigid ice that is carried along on the plastically flowing lower ice. Because they are near melting point, valley glaciers do not have to be very thick to flow—a little over

30 m may be sufficient. The depth of the crevasses marks the threshold between brittle and plastic ice—at which level the yield stress¹ is reached. By contrast, a great stress is required to cause flow if the temperatures are very low as in polar glaciers.

Though the direction of movement of the terminus of a glacier is the simplest indicator of where the balance of accretion and ablation lies, this in itself tells us nothing about the *cause* of any change.

Himalayan glaciers present a distinctive variation of the typical flow mode. Whereas many glaciers start from icecaps that flow to the terminus, with continuous flow from the snow-collecting area to the glacier snout, many of those in the Himalayas are avalanche-fed. Relief is so great, and the peaks are so sharp, that snow falling on the peaks reaches the glaciers in the valleys via avalanches. The growth of such glaciers depends not just on precipitation, then, but on the frequency of avalanches. It could happen, for example, that increased temperature in the mountains caused increased avalanching, thereby thickening the glaciers and causing increased flow.

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¹ The *yield stress* in ice is the stress above which behavior changes from that of a solid with brittle (elastic) properties to a material with ductile flow.

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5.2 Glaciers as Paleo-thermometers

Temperature not only affects flow rates in glaciers but also plays a critical role in the accumulation and ablation of snow and ice that control whether glacier termini advance or retreat.

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation dominates in the winter, ablation in the summer. If the two are equal, then the net balance of the glacier is zero; if accumulation is greater, the net balance will be positive; and if ablation is greater, the net balance will be negative.

A glacier having a protracted negative net mass balance loses ice not only by retreat of the terminus but also by substantial thinning or downwasting of the glacier. Because rates of glacial movement are a function of ice thickness, thinning of the ice reduces the rate of ice transfer down glacier, and the rate of retreat and downwasting increases. Thus, acceleration of terminal retreat in a glacier does not necessarily indicate accelerated climatic warming. Nonetheless, because climatic factors control accumulation and ablation rates, glaciers are often used as indicators of past climatic conditions. Figure 5.2.1 illustrates the relationship between climate and glacial response.

Reference

Easterbrook, D.J. 1993. *Glacial Processes; Surface Processes and Landforms*. Prentice Hall, p. 293–332.

5.3 Modern Global Ice Volume and Mass Balance

Ice is naturally present on Earth's surface in three main geomorphic forms: land-based icecaps (Greenland and Antarctica), mountain-valley glaciers, and floating sea ice. Today, nearly 30 million km³ (91 percent) of all land ice is in Antarctica, 2.6 million km³ (8 percent) is in Greenland; all other valley glaciers added together have a volume a little less than 0.2 million km³ (0.6 percent) (Poore *et al.*, 2011). Any consideration of the global ice budget, and changes within it, must start by acknowledging these bounding parameters of ice distribution.

Of the approximately 160,000 glaciers currently known to exist, only 67,000 (42 percent) have been inventoried to any degree (Kieffer *et al.*, 2000). Mass balance data (net positive for glacier growth, negative for shrinkage) exist for more than a single year for only just over 200 glaciers (Braithwaite and Zhang, 2000). When the length of record increases to five years, this number drops to 115; if both winter and summer mass balances are required, the number drops again to 79. Only 42 glaciers have records longer than 10 years. "That many glacierized regions of the world remain unsampled, or only poorly sampled" (Braithwaite and Zhang, 2000) represents a major problem for those wishing to undertake accurate global mass balance research.

Clearly, we know very little about the true state of most of the world's glaciers. Moreover, and despite media alarmism about the issue, mountain glaciers worldwide contain just 45 cm of sea-level change equivalent, and their melting is therefore largely irrelevant to concerns about sea-level rise. Major sea-level change from melting ice depends practically on the relative ice balance of the large Antarctic (73 m sea-level equivalent) and Greenland (7 m sea-level equivalent) icecaps (Poore *et al.*, 2011).

It is useful to distinguish two main lines of evidence as to whether modern changes in the mass balance of the cryosphere are unusual. The first of these is a comparison of modern with historic and



Figure 5.2.1. Relationship between and among climate, accumulation/ablation, net mass balance, and position of a glacier terminus. Adapted from Easterbrook, D.J. 1993. *Glacial Processes; Surface Processes and Landforms*. Prentice Hall, pp. 293–332.

Holocene changes in mountain glaciers, back to 11,700 years BP. It is, for example, well established that major glacial advances occurred between the fifteenth and nineteenth centuries, during a period of colder global temperature known as the Little Ice Age (Broecker, 2001; Grove, 2001). Many records indicate widespread glacial retreat thereafter, as temperatures began to rise in the mid- to late-1800s, and many glaciers have since shrunk in size and returned to a position characteristic of their pre-Little Ice Age state.

Second is the question of whether modern glaciers and icecaps are in a uniform, or indeed accelerating, state of retreat, as many commentators have alleged. The detailed evidence regarding this is presented below under the appropriate headings. To date, however, no research has contradicted the findings of Dowdeswell *et al.* (1997) and Braithwaite (2002).

In an analysis of Arctic glacier mass balance, Dowdeswell *et al.* (1997) found that of the 18 glaciers with the longest mass balance histories, more than 80 percent displayed negative mass balances over their periods of record. In addition, “almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance.” Because of the multiple warm and cool periods of the past century—two periods of cooling (1880–1915 and 1945–1977) and two periods of warming (1915–1945 and 1978–1998)—glaciers have both advanced and retreated. No global warming has occurred since 1998 and glaciers appear to be in a transition period.

Braithwaite (2002) reviewed mass balance measurements of 246 glaciers made between 1946 and 1995, spanning both the 1946–1977 cool period and the 1978–1998 warm period. He found “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 “Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980–95.” When results for the whole world are combined for this most recent period of time, Braithwaite notes “there is no obvious common or global trend of increasing glacier melt in recent years.”

The glacier with the longest mass balance record is the Storglaciaren glacier in northern Sweden. The first 15 years of its 50-year record showed a negative mass balance with little trend. Thereafter, however, its mass balance became positive during the latter part of the 1945–1977 cool period (Braithwaite and

Zhang, 2000).

Although glaciers have advanced and retreated during alternating warm and cool periods, since the Little Ice Age (LIA) glaciers have lost mass as Earth thawed. No “unprecedented warming” occurred in the latter part of the twentieth century. Rather, glaciers retreated strongly during the 1915–1945 warm period before major industrial CO₂ emission and advanced during the 1945–1977 cool period when CO₂ emissions were soaring—just the opposite of what should have happened if CO₂ caused global warming and glacial melting.

Conclusion

No substantive evidence exists that the rate of glacier retreat has increased over the past 70 years, a time of large increases in CO₂ emissions. The common claim that most glaciers are today retreating or melting in response to human carbon dioxide emissions is incorrect. The global data on glacial mass balance simply do not support the claims made by the IPCC that most glaciers are today retreating or melting.

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M., Johansson, M., Kaab, A., Koenig, M., Konovalov, V., Maisch, M., Paul, F., Rau, F., Reeh, N., Rignot, E., Rivera, A., Ruyter de Wildt, M., Scambos, T., Schaper, J., Scharfen, G., Shroder, J., Solomina, O., Thompson, D., Van der Veen, K., Wohlleben, T., and Young, N. 2000. New eyes in the sky measure glaciers and ice sheets. *EOS: Transactions, American Geophysical Union* **81**: 265, 270–271.

Poore, R.Z., Williams, R.S., and Tracey, C. 2000 (revised 2011). Sea level and climate. United States Geological Survey (USGS) Fact Sheet 002–00. <http://pubs.usgs.gov/fs/fs2-00/>.

5.4 Antarctic Ice Cap

Antarctica covers 14.0 million km² (5.4 million sq mi) and is Earth's fifth-largest continent (see Figure 5.4.1). Glacial ice covers about 98 percent of Antarctica. It is the coldest, driest, and windiest continent and has the highest average elevation of all the continents. Antarctica has about 91 percent of the world's ice, representing about 70 percent of the world's fresh water.

Antarctica is also by far the coldest continent, with the coldest temperature ever recorded being -89.2 °C at the Russian Vostok Station on July 21, 1983. Temperatures in the interior are often -80°C with low precipitation, making Antarctica a frozen desert. The South Pole averages less than 10 cm of snow per year.

East Antarctica, the highest part of the continent, is covered by the East Antarctic Ice Sheet, which reaches thicknesses of 4,776 m with a mean thickness of 2,225 m. At its lowest point Antarctica is 2,480 m below sea level.

West Antarctica makes up a much smaller area and is covered by the West Antarctic Ice Sheet. The West Antarctic Peninsula extends northwest from the main continent (see Figure 5.4.1) and contains only a small proportion of the total ice in Antarctica.

The study of Antarctica's climate has provided valuable insights and spurred contentious debate over issues of global climate change. Climate model results project warming for polar regions under enhanced greenhouse gas emissions, leading many to anticipate Earth's polar regions will experience severe responses to rising CO₂ levels. Real-world data from Antarctica do not support such expectations. In the 2009 and 2011 NIPCC reports, scientific analyses are described that demonstrate nothing unusual, unprecedented, or unnatural about the present climate of the large Antarctic ice sheet.

Among the commonest lines of evidence cited for

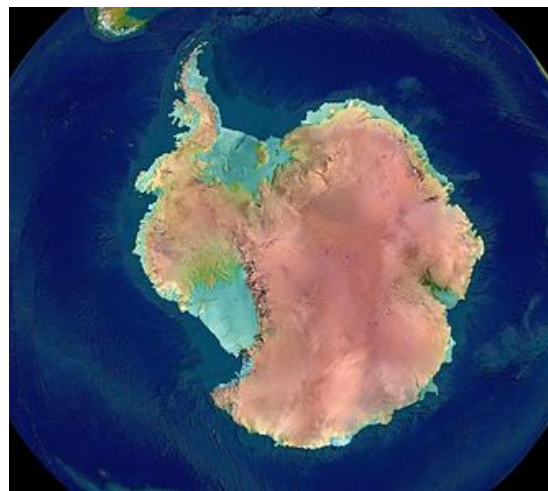
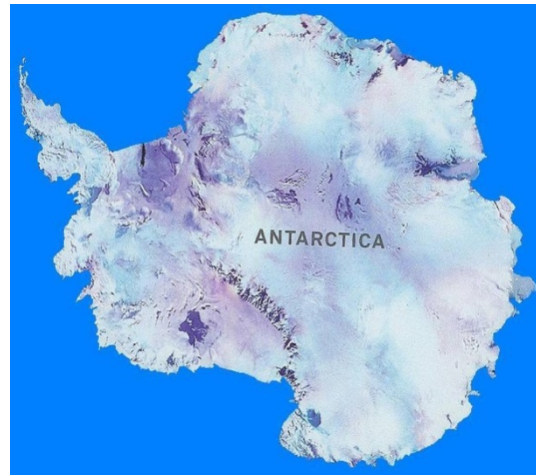


Figure 5.4.1. UPPER. Satellite view of the Antarctic Ice Sheet. LOWER. Digital terrain map of the subglacial rock topography of Antarctica, colored as to height, after removal of the ice and correction for isostatic rebound and sea level change (NASA images).

unusual melting of Antarctic ice is the breaking away of large pieces of glacier termini or ice shelf. Warm ocean water around the West Antarctic Peninsula regularly causes some melting of ice and breaking off of pieces of shelf ice, but the volumes affected are only a small percentage of the main Antarctic ice sheet. The glaciological processes involved are entirely normal and natural; no evidence has been found to show the process of glacial calving around Antarctica is any different today than in the past.

For example, in November 2001 a large iceberg separated from West Antarctica's Pine Island Glacier. This event created great interest because the Pine Island Glacier is the fastest-moving glacier in Antarctica and discharges the largest volume of ice. Some speculated this event might herald the

“beginning of the end” of the West Antarctic Ice Sheet. Scientific studies 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 four years. Subsequently, Stenoien and Bentley (2000) used radar altimetry and synthetic aperture radar interferometry to prepare a velocity map of the ice catchment region, which revealed a system of tributary ice-flow streams that feed the main, fast-flowing trunk glacier. By combining velocity data with ice thickness and snow accumulation rates, they calculated an approximate mass balance for the glacier with an uncertainty of $\sim 30\%$. Their results suggested the mass balance of the catchment region was not significantly different from zero during recent years.

Hall (2009) concludes for many localities around Antarctica “ice extent was less than at present in mid-Holocene time,” suggesting “the magnitude of present ice recession and iceshelf collapse is not unprecedented.”

Evidence for previous ice shrinkage during warmer parts of the Holocene in the western Ross Sea region has been provided by Hall and Denton (1999, 2002) based on the distribution and dating of surficial and terrace deposits. Their research shows “the Wilson Piedmont Glacier was still less extensive than it is now” during the Medieval Warm Period. Together with Baroni and Orombelli (1994a), they also provided evidence for “an advance of at least one kilometer of the Hell’s Gate Ice Shelf within the past few hundred years.”

Hall and Denton conclude the Ross Sea area evidence suggests “late-Holocene climatic deterioration and glacial advance (within the past few hundred years) and twentieth century retreat.” Comparison with dated moraines elsewhere in the world shows the reported Wilson Glacier advance overlaps with similar Little Ice Age advances known from the South Shetland Islands (Birkenmajer, 1981; Clapperton and Sugden, 1988; Martinez de Pison *et al.*, 1996; Björck *et al.*, 1996), New Zealand (Wardle, 1973; Black, 2001), and even Europe.

Further support for a Holocene history punctuated by ice advance and retreat is provided by Hall’s (2009) comprehensive circum-Antarctic review, which found “glaciers on most if not all” of the Indian/Pacific-sector sub-Antarctic Islands “underwent advance in the last millennium, broadly synchronous with the Little Ice Age,” and “glaciers in

all areas” have “subsequently undergone recession,” but only in “the past 50 years.”

Tedesco and Monaghan (2010) studied records collected since the launch of passive microwave radiometers in 1979, finding for the past three decades the continent-wide snow and ice melting trend has been “negligible.” They also report between 1979 and 2009 snow and ice melt was at a “record” low, marking a “new historical minimum”; “December 2008 temperature anomalies were cooler than normal around most of the Antarctic margin”; and the “overall sea ice extent for the same month was more extensive than usual.”

Vaughan *et al.* (2003) note “historical observations since 1958 at Esperanza Station document warming equivalent to $3.5 \pm 0.8^\circ\text{C}$ per century,” marking the Antarctic Peninsula as among the most rapidly warming regions on Earth. To establish whether this warming is unusual in any way, Mulvaney *et al.* (2012) analyzed deuterium/hydrogen isotope ratios (δD) of an ice core from James Ross Island at the northeastern tip of the Antarctic Peninsula to develop a late glacial and Holocene temperature history for the region. They found the Antarctic Peninsula experienced a Holocene warm period 9,200–2,500 years ago, similar to modern-day levels. They also found “the high rate of warming over the past century is unusual (but not unprecedented) in the context of natural climate variability over the past two millennia.” More specifically, the temperature of James Ross Island has increased by $1.56 \pm 0.42^\circ\text{C}$ over the past 100 years, and at a rate of $2.6 \pm 1.2^\circ\text{C}$ over the past half-century. Mulvaney *et al.* conclude this is “highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era.”

Conclusions

These studies establish that on the shorter, meteorological time scale the Antarctic ice mass is effectively stable.

On the longer-term climatic scale, glacial activity on and around Antarctica has fluctuated in parallel with the millennial-scale ice volume variability evident throughout the world, including recession during the Medieval Warm Period to positions that have not been attained again today, followed by significant advances during the intervening Little Ice Age and recession again during the nineteenth and twentieth century natural warming episode.

Moreover, the modern warming of the Antarctic Peninsula falls within the bounds of natural variation during the Holocene.

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5.5 Greenland Ice Cap

Only a small part of global ice volume is represented today by the Greenland Ice Cap (8 percent of the total), and during the last great glaciation, 20,000 years ago, the Greenland massif comprised an even smaller part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Despite its small size, an understanding of the controls on formation and melting of the Greenland Ice Cap remains important. Interest in Greenland and other Arctic ice-covered areas is also much enhanced by the nearby presence of Scandinavian and North American countries, whose citizens are alert to the conservation of their Arctic environment and its biota, including iconic species such as the polar bear.

The topographic map of the Greenland Ice Cap shows a broad dome, leading to the common assumption that the icecap is underlain by a dome-shaped continent. A map of the base of the ice shows this is not true. Instead a kilometer-deep basin extends below sea level under the Greenland interior, the sub-ice terrain being a bowl formed by a ring of mountains with few openings to the sea. This results from the mass of the icecap being heavy enough to cause isostatic sinking of the land.

Importantly, therefore, the ice cannot simply slide into the sea as is often alleged. Instead, ice near the base of the icecap flows upwards to join glaciers flowing through gaps in the mountain rim. According to the IPCC's *Fourth Assessment Report*, melting of the whole ice sheet would contribute nearly 7 m to sea-level rise (Bergmann *et al.* 2012). Yet if the whole ice sheet could suddenly melt, much of the water would be retained in a huge lake bounded by

the mountain rim. In any case, the distribution of annual mean temperatures on Greenland is such that melting is possible only around the periphery (Figure 5.5.1).

In 2006, several commentaries and articles in a celebrated issue of *Science* magazine described accelerating discharges of glacial ice from Greenland and gave dire warnings of an imminent large, rapid, and accelerating sea-level rise as one result (Bindschadler, 2006; Ekstrom *et al.*, 2006; Joughin, 2006; Kerr, 2006; Kennedy and Hanson, 2006; Otto-Bliesner *et al.*, 2006; Overpeck *et al.*, 2006). The center of the discussion was Ekstrom *et al.*'s identification of a 2002–2005 increase in micro-earthquakes beneath outflowing glaciers on the east and west coasts of Greenland, between approximately 65°N and 76°N latitude, which they argued indicated enhanced and potentially dangerous glacial flow.

The implied conclusion from the *Science* papers—that the changes were the result of human-caused global warming—was not shared by Joughlin (2006), who showed summer temperatures at locations within the glacial earthquake area were warmer during the 1930s than in 2002–2005. Joughlin concluded the period of recent warming in Greenland “is too short to determine whether it is an anthropogenic effect or natural variability.”

Przybylak (2000) published a comprehensive meteorological analysis that provides strong support for Joughlin's conclusion, stating, “the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century” and citing corroborating evidence for an earlier warm Arctic in the 1930s and 1950s. Przybylak's concluded 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 “the temperature predictions produced by numerical climate models significantly differ from those actually observed.” These conclusions are supported by Greenland temperature records dating back to 1880 (Figure 5.5.2).

The studies discussed so far fail to take adequate account of the Holocene context within which modern glacial change must be considered. The record indicates warmer temperatures were the norm in Greenland in the earlier part of the past 4,000 years, including century-long intervals nearly 1° C warmer than the recent decade of 2001–2010 (Chylek *et al.*, 2004, 2006; Easterbrook, 2011). The current decadal mean temperature in Greenland has not exceeded the

envelope of natural variability over the past 4,000 years.

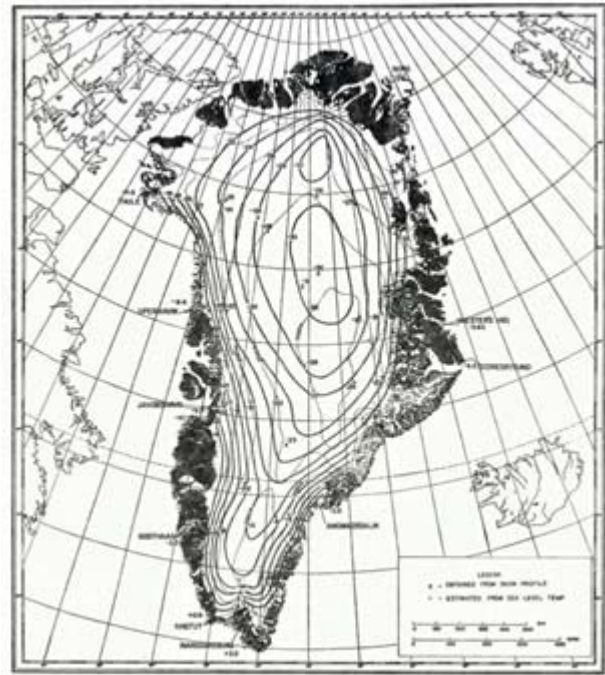


Figure 5.5.1. Mean annual temperature on the Greenland Ice Cap. Ice melting can only occur where the temperature exceeds the melting point. These conditions only occur at the edges of the icecap, where continued melting depends on glacially-slow flow to replace the melted ice. Adapted from Box, J.E., Yang, L., and Bromwich, D.H. 2009. Greenland Ice Sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.

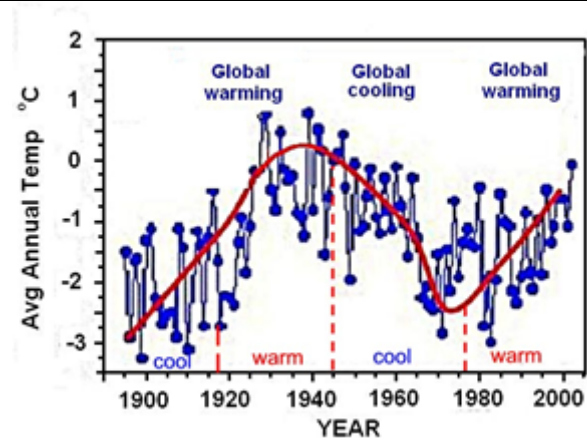


Figure 5.5.2. Temperatures in Angmagssalik, Greenland, since 1890, showing a multidecadal pattern of warmings and coolings. Note temperatures in the 1930s were higher than modern temperatures. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221.

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Kobashi *et al.* (2011) reconstructed high-resolution (~10 yr) records of the past 1,000 and past 160 years of Greenland's snow surface temperature, which also delineate clear multidecadal to multicentennial temperature fluctuations (see Figure 5.5.3). In keeping with more generalized climatic histories, these records are characterized by a warm period in the eleventh and twelfth centuries (the Medieval Warm Period), a long-term cooling toward the coldest period in the seventeenth and eighteenth centuries (the Little Ice Age), and the observed most recent warming (1978–2000).

Greenland underwent a 33 percent greater warming in 1919–1932 than the warming in 1994–2007 (Box *et al.*, 2009), and the recent decadal average temperature is similar to that of the 1930s–1940s (Chylek *et al.*, 2006; Box *et al.*, 2009). Kobashi *et al.* (2011) note the 2000–2010 decadal average surface temperature at the Greenland ice sheet summit, the warm period of the 1930s–1940s, and the Medieval Warm Period indicate “the present decade is not outside the envelope of variability of the last 1000 years.”

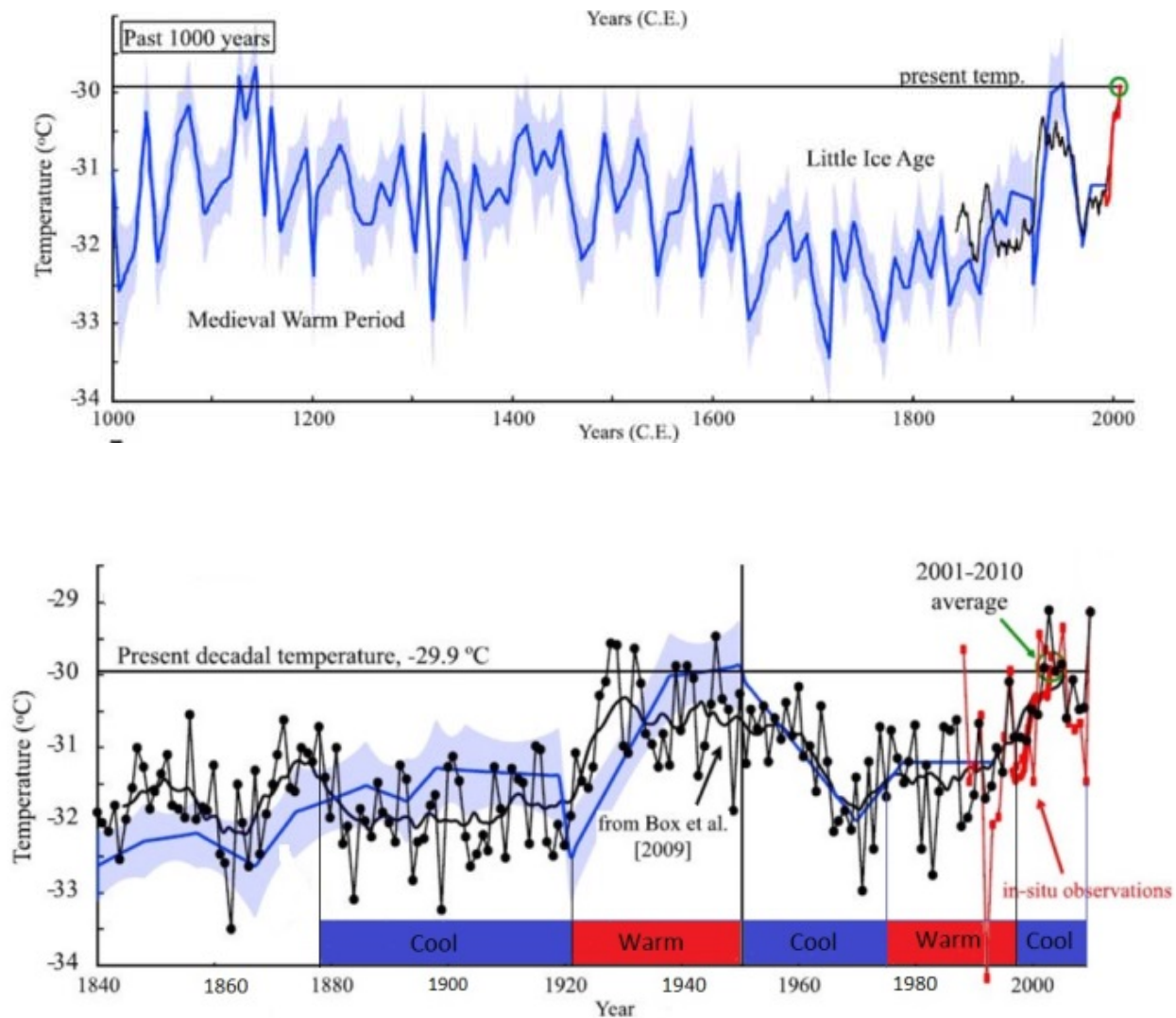


Figure 5.5.3. Reconstructed Greenland snow surface temperatures for the past 4000, 1,000 and 160 years. The alternating warm and cool periods correlate well with measured temperatures and other reconstructions. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

Conclusion

The temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years. Recent warmth is not unprecedented, and none of it was necessarily caused by rising CO₂.

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Other research

A number of recent publications on the ice history of Greenland and nearby islands have demonstrated significant ice loss occurred in the twentieth century, in some part during periods of strong warming.

- Mernild *et al.* (2008) describe the 1993–2005 glacial history of Mittivakkat Glacier, on Ammassalik Island, Greenland, as having an overall “mass balance (that) has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% per year.” This and earlier ice loss occurred against the background of instrumental warmings recorded for 1918–1935 at 0.12°C per year and for 1978–2004 at 0.07°C per year.” These authors also report “the warmest average 10-year period within the last 106 years was the period from 1936–1946 (-1.8°C),” while the second warmest period was from 1995–2004 (-2.0°C). In addition, they note the period 1936–1946 was the warmest period within the last 106 years in West Greenland (Cappelen, 2004).

- Frauenfeld *et al.* (2011) also report Greenland ice melt has been increasing during the past three decades, with the melt extent observed in 2007 being the greatest on record as observed from satellite records. They comment the “total annual observed melt extent across the Greenland ice sheet has been shown to be strongly related to summer temperature measurements from stations located along Greenland’s coast, as well as to variations in atmospheric circulation across the North Atlantic.”

To test whether these changes might represent unprecedented modern (and anthropogenic) warming, Frauenfeld *et al.* reconstructed a record of annual ice melt extent across Greenland that extends back for 226 years, combining more recent satellite-derived observations with older melt extent values based upon historical observations of summer temperatures and winter circulation patterns. They conclude “the recent period of high-melt extent is similar in magnitude but, thus far, shorter in duration than a period of high melt lasting from the early 1920s through the early 1960s.” Although the greatest recorded melt extent did indeed occur in 2007, the occurrence was not statistically

significantly different from 20 older melt seasons, most during 1923–1961.

Frauenfeld *et al.* note “there is no indication that the increased contribution from the Greenland melt in the early to mid-20th century ... resulted in a rate of total global sea level rise that exceeded ~3 mm/yr.” Instead, their results indicate “Greenland’s contribution to global sea level rise, even during multi-decadal conditions as warm as the past several years, is relatively modest.”

- A common worry regarding ice wastage is that in summer surficial meltwater will penetrate through crevasses to lubricate faster flow at the base of the glacier (Iken and Bindschadler, 1986; Mair *et al.*, 2002; Truffer *et al.*, 2005; Bamber *et al.*, 2007; Bartholomew *et al.*, 2008; van de Wal *et al.*, 2008; Shepherd *et al.*, 2009; Schoof, 2010; Sundal *et al.*, 2011). Given that much glacier flow occurs by intracrystalline plastic processes, this worry is based on the speculative assumption of additional flow by sliding along the glacier-bedrock contact. Hoffman *et al.* (2011) have reported “basal lubrication by surface meltwater penetrating the Greenland Ice Sheet generates summer speedups of 50-200% for the regions of the ablation zone experiencing sheet flow.”

To investigate this phenomenon further, Hoffman *et al.* compared temperature measurements made at two weather stations; episodic supraglacial lake drainage events observed on Landsat images made at fortnightly intervals between early June and late August 2007; and ice velocity as recorded at nine GPS stations located across a 50 km swath of the western Greenland Ice Sheet. Calculation of strain rates and bed separation demonstrated the occurrence of “an early summer background period of constant ice velocity in west Greenland, followed by a speedup that lasted most of the summer and was associated with surface melt.” They also found “areas in the ablation zone typically experienced [only] one to two velocity events that are inferred to result from supraglacial lake drainage” and “in all cases the effects are short-lived (less than one day) and local (less than 10 km).” It is therefore unlikely rising temperatures are able to generate a positive feedback that causes significant glacial mass loss. Though Hoffman *et al.* say “episodic pulses of water are key for generating enhanced sliding,” they add “these daily increases in velocity are superimposed on a night time velocity that generally decreases over the season ... support(ing) the idea that rising air temperatures in Greenland may not translate directly into increased sliding at the seasonal scale.” Similar results have been reported by earlier writers,

including Zwally *et al.* (2002), Joughin *et al.* (2008), van de Wal *et al.* (2008), Shepherd *et al.* (2009), Bartholomew *et al.* (2010), Sundal *et al.* (2011), and Palmer *et al.* (2011).

Conclusions

It has been claimed that CO₂-induced global warming should be expressed most strongly in the Arctic, and its effects therefore should be evident there before anywhere else, making the Arctic the “canary in the coal mine” for those concerned about dangerous global warming. Though some localities in Greenland did indeed record significant ice retreat during the twentieth century, at other places, such as the Flade Isblink Ice Cap, ice accreted in sufficient amounts to cancel out the ice loss elsewhere.

The studies reported above make clear that any recent upswing in glacial outflow activity on Greenland has no necessary or likely relationship with anthropogenic global warming, as late twentieth century temperatures did not rise either as fast or as high as they did during the great natural warming of the 1920s–1930s.

The spectacular, and therefore often filmed, coastal glacial collapses or surficial meltwater streams plunging into crevasses represent only half of the equation relating to ice-sheet “collapse” and threatened sea-level change, the other half being the rate of inland ice accumulation derived from snow precipitation. Recent satellite radar altimetry suggests Greenland is in a state of approximate mass balance, quite contrary to the alarmist tone of the 2006 *Science* studies.

The argument that the modern Greenland Ice Cap is melting under the influence of anthropogenic warming is also greatly weakened by new stratigraphic evidence for Eocene-Oligocene ice in the Northern Hemisphere (Eldrett *et al.*, 2007), 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.” We now have evidence of a much warmer period of time during which the Greenland Ice Sheet failed to melt. In addition, “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.”

The Little Ice Age lasted in Greenland until 1918, longer than it did in many other places, which doubtless helped to achieve a post-LIA rate of

warming between 1918 and 1935 some 70 percent greater than the warming from 1978 to 2004—even though the mean rate-of-rise of the atmosphere’s CO₂ concentration in the late twentieth century was nearly five times greater than during the 1920s–1930s warming. Greenland experienced more rapid warming in the earlier period of slow CO₂ rise, and slower warming in the latter period of rapid CO₂ rise.

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5.6 Other Arctic Glaciers

A perception existed until recently that high Arctic glaciers, especially those in Iceland and Svalbard (Spitzbergen), have been uniformly undergoing a reduction in ice volume since the mid-1990s.

Rinne *et al.* (2011) used satellite-borne radar altimetry to map elevation changes of the Flade Isblink Ice Cap (FIIC), northeast of Greenland, between 2002 and 2009. FIIC is the largest icecap in Greenland separate from the Greenland Ice Sheet, covering an area of 8,500 km². The measurements showed elevation gain (ice accretion) of up to 2 m/yr over most of the icecap, and elevation loss of up to 1 m/yr (ice melting) in lower, peripheral areas. The authors also reported a thickening, and inferred slowing of flow, of three outlet glaciers northeast of Station Nord. This confirmed the findings of Joughin *et al.* (2010), who, based on satellite-measured velocities, reported a slowdown from 300 m/year to 60 m/year for two of these glaciers between 2000 and 2006. Overall, Rinne *et al.* found “the net mass change rate of the FIIC to have been zero (0.0 ± 0.5 Gt/year) during 2002–2009.”

Rolsted Denby and Hulth (2011) used geodetic data derived from optical imaging back to 1949 to determine whether such reductions also applied to Jan Mayen Island, a 373-km² glaciated volcanic island located in the North Atlantic Ocean between Iceland and Svalbard at latitude 71° N. They found over the 33-year period 1975–2008 the ice volume in the southern part of Jan Mayen Island increased; there was also an increase in ice volume over the 59-year period 1949–2008, although the result was not statistically significant. These increases occurred despite a parallel increase in the annual mean temperature of the region by 1.58°C over the past 30 years, which drove a peripheral sea-ice retreat.

This combination of circumstances suggests where warming prevents winter sea-ice formation, the extra moisture made available by evaporation can enhance precipitation (in the form of snowfall) on coastal glaciers, and hence their growth even in a warming environment.

Moholdt *et al.* (2012) used data from the Ice, Cloud, and Land Elevation Satellite (ICESat) and the GRACE gravity satellites to assess the glacier mass budget between October 2003 and October 2009 for a

total glaciated area of 51,500 km² in the Russian High Arctic (Franz Josef Land, Severnaya Zemlya, and Novaya Zemlya). Their results were placed in a slightly longer-term climatic context by consideration of meteorological data from 1980 to 2009. As shown in Figure 5.6.1, significant glacial mass loss has occurred on Novaya Zemlya, less in Severnaya Zemlya, and a marginal increase in Franz Josef Land. All three records show a tendency for an increase in ice mass over the last two years. Of course, no hard conclusions can be reached on the basis of such a short and variable record; moreover, much uncertainty is attached to studies that utilize GRACE data because of the uncertainty of current geoid models (Houston and Dean, 2012).

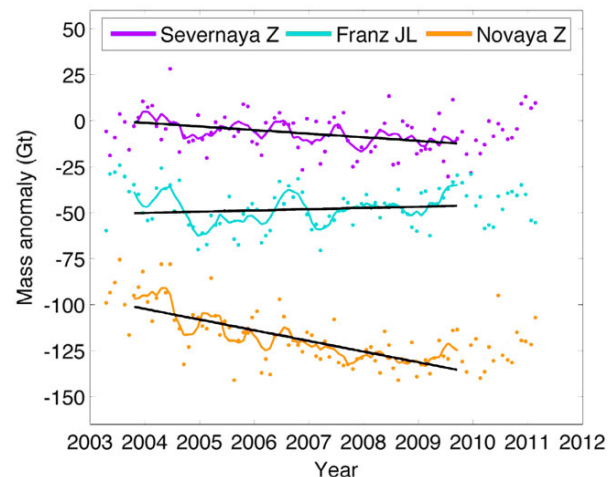


Figure 5.6.1. Monthly glacier mass anomalies (dots) as determined from GRACE, where colored curves are five-month running means of monthly data and black lines are linear fits to the monthly data within the ICESat for October 2003–October 2009. Adapted from Moholdt, G., Wouters, B., and Gardner, A.S. 2012. Recent mass changes of glaciers in the Russian High Arctic. *Geophysical Research Letters* **39**: 10.1029/2012GL051466.

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Earlier research

Here we provide brief summaries of earlier published and NIPCC-summarized evidence for historic trends in Arctic glacier behavior, to see if it corresponds to the pattern of melting and retreat predicted by IPCC modeling.

- Dowdeswell *et al.* (1997) analyzed the mass balance records of the 18 Arctic glaciers with the longest observational histories, 80 percent of which displayed negative mass balances over their period of measurement. Ice core records from the Canadian High Arctic islands support this finding, and the researchers concluded 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.”
- Calkin *et al.* (2001) provide a comprehensive review of Holocene glaciation along the northernmost Gulf of Alaska, between the Kenai Peninsula and Yakutat Bay. Several periods of glacial advance and retreat are identified over the past 7,000 years. A general ice retreat during the Medieval Warm Period lasted for “at least a few centuries prior to A.D. 1200,” after which the three major intervals of Little Ice Age—in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century—were accompanied by glacial expansion and depression of ice equilibrium-line altitudes by 150–200 m below present values.
- Zeeberg and Forman (2001) analyzed twentieth century changes in glaciers on north Novaya Zemlya—a Russian island located between the Barents and Kara Seas in the Arctic Ocean. Here, an accelerated post-Little Ice Age glacial retreat occurred in the first and second decades of the twentieth century. By 1952 the region’s glaciers had experienced 75 to 100% 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 began to advance. Instrumental records show the most recent of these glacial stabilizations and advances occurred in response to

increases in precipitation and/or decreases in temperature.

- Mackintosh *et al.* (2002) described 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, after which it retreated to a minimum length of 13.2 km in 1783. Rebounding rapidly, the glacier returned to its 1705 extent by 1794 and its 1740 length by 1820. This maximum length was maintained for the next half-century, after which the glacier contracted slowly to lengths of 14.75 km in 1932 and 13.8 km in 1970, after which rapid expansion occurred to 14.3 km by 1995. Currently, the glacier terminus falls about midway between its maximum and minimum positions of the past three centuries, and Mackintosh *et al.* report “the recent advance (1970–1995) resulted from a combination of cooling and enhancement of precipitation.”

- Humlum *et al.* (2005) evaluated the climate dynamics of high-latitude glaciers in the Svalbard Archipelago, especially the Longyearbreen glacier in arid central Spitzbergen (latitude 78°13’N). They found the Longyearbreen glacier “has increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years,” and they suggest this late-Holocene glacial growth is probably widespread in Svalbard and adjoining Arctic regions. Climate in Svalbard changed sharply more than once in the twentieth century, with Arctic-record rates of temperature rise in the early 1920s, followed by a nearly equivalent temperature drop four decades later. The Longyearbreen glacier changed in concert, and the current position of its terminus suggests this region of the Arctic is currently experiencing some of the lowest temperatures of the entire Holocene at a time of high atmospheric CO₂ concentration.

- In a late Holocene study, Bradwell *et al.* (2006) examined the link between fluctuations of Lambatungnajokull glacier, southeast Iceland, and variations in climate. Comparison between the glacial history and instrumental records show over the past four centuries “there is a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat”; recession was greatest during the 1930s and 1940s, when it averaged 20 m/year, but thereafter it slowed so “there has been little overall retreat since the 1980s.” The twentieth century part of this glacial history is shared by other nearby glaciers, consistent with the full 400-year history being typical for the wider region.

Conclusions

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO₂-induced global warming. These signs were expected to become especially evident in the second half of the twentieth century, when approximately two-thirds of the rise in industrial CO₂ emissions occurred and Earth's temperature allegedly rose to unprecedented levels.

The evidence is clear regarding these postulates: The many papers summarized above do not find high Arctic glaciers are uniformly wasting away. Instead, as some glaciers advance, others retreat, with the Jan Mayen example showing as well that some advances are actually accompanied by warming rather than cooling. Changed precipitation is as commonly a cause of glacial change as is changed temperature.

In particular, the findings of Humwell *et al.* (2005) and Bradwell *et al.* (2006) suggest in some Arctic regions twentieth century air temperatures peaked in the 1930s and 1940s, 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 steady warming claimed by the IPCC to have occurred around the globe through the twentieth century and especially over the last four decades. That empirical data from the Arctic should contradict this thesis so thoroughly is embarrassing for computer modellers, who have persistently predicted it is the high-latitude regions where anthropogenic global warming should be earliest and most strongly expressed. Clearly the real glacial world is more complex than IPCC computer models allow.

To the degree that in some regions (e.g., the Canadian Arctic) most glaciers have retreated over the past 150 years, this is no more than would be expected for glaciers emerging from the Little Ice Age. This circumstance does not require CO₂ emissions as an additional explanation.

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5.7 The Long Ice Core Record

The large ice sheets of Antarctica and Greenland contain a remarkable record of past climatic changes, accumulated in their layered ice over tens to hundreds of thousands of years (Figure 5.7.1).

These deep ice cores have yielded much critical information about past climatic changes. The ¹⁸O/¹⁶O ratios in the ice can be used to identify past climatic changes, including proxy air temperature; analysis of trapped gases in the ice allows estimation of the ancient CO₂ content of the atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric parameters can also be determined from the ice.

The ice core data clearly show the climate record is permeated and punctuated by rapid climate changes, including short, abrupt climate swings with surprisingly high rates of warming and cooling (e.g., Steffenssen *et al.*, 2008). That the ice core data are indeed a proxy for global climate change is apparent because fluctuations of glaciers all over the world match the climatic events shown in both deep sea mud cores and other ice cores. These results notwithstanding, some scientists remain skeptical of the accuracy of geochemical measurements made in ice cores because of envisaged problems of post-depositional gas migration and ice bubble diffusion, leakage, and fractionation (e.g., Jaworowski *et al.*, 1992).

The most precisely dated ice cores are from the Greenland Ice Sheet Project (GISP) and Greenland Ice Core Project (GRIP). These cores are especially important because the age of the ice at various levels in the core can be measured by counting annual layers

in the ice, giving a very accurate chronology. The GISP2 Greenland ice core has proven to be a great source of climatic data from the geologic past. The oxygen isotope ratios of thousands of ice core samples were measured by Minze Stuiver and Peter Grootes at the University of Washington (e.g., Grootes and Stuiver, 1997), and these data have delineated what has become to be accepted as a world standard climatic record.

The ratio of ^{18}O to ^{16}O in an ice core sample depends upon the temperature when the snow crystallized and is later transformed into glacial ice. Ocean volume also may play a role in $\delta^{18}\text{O}$ values, but these measurements nonetheless provide a good proxy for ancient temperature, with the age of each sample being accurately known from annual dust layers in the ice core.

Changes in carbon dioxide content lag their equivalent temperature events by between several

hundred and 2,000 years in Antarctic ice cores (see Figures 5.7.1 and 5.7.2). Changes in carbon dioxide level cannot be the proximate cause of the warmings and coolings seen. Fischer *et al.* (1999) established CO_2 lagged temperature by 600 ± 400 years as the climate warmed from an ice age. Monnin *et al.* (2001) found warming from the last major ice age preceded rise in CO_2 by 800 ± 600 years. Caillon *et al.* (2003) documented that rise in temperature preceded rise in CO_2 in the Vostok core by 800 ± 200 years. Mudelsee (2001) recognized temperature over the past 420,000 years preceded changes in CO_2 by $1,300 \text{ years} \pm 1,000$ in the Vostok core. Petit *et al.* (1999) analyzed 420,000 years of the Vostok core and found as the climate cooled into an ice age, the CO_2 decrease lagged by several thousand years.

Measurements of recent and modern temperature and CO_2 changes show the same lead-lag effect (Figure 5.7.3).

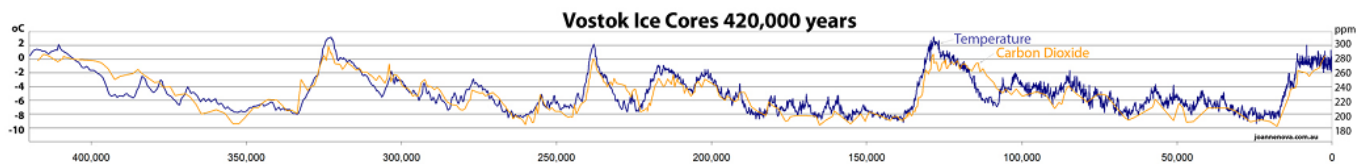


Figure 5.7.1. Temperature and CO_2 for 100,000–150,000 years ago from the Vostok ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. Reprinted from Joanne Nova, 2013, <http://joannenova.com.au/global-warming-2/ice-core-graph/>.

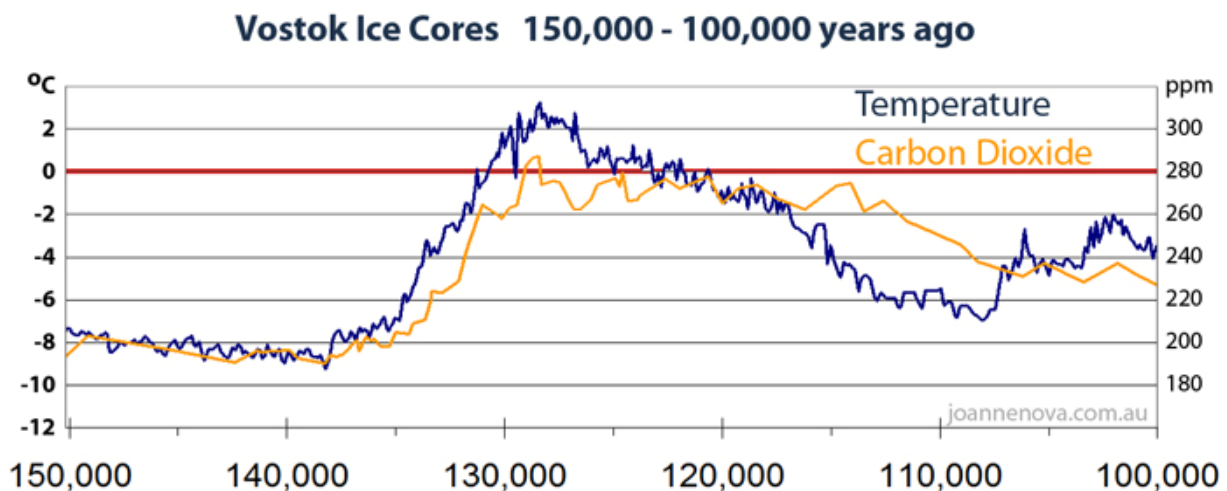


Figure 5.7.2. Temperature and CO_2 levels detail for 100,000–150,000 years ago from the Vostok ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. From Joanne Nova, 2013, <http://joannenova.com.au/global-warming-2/ice-core-graph/>.

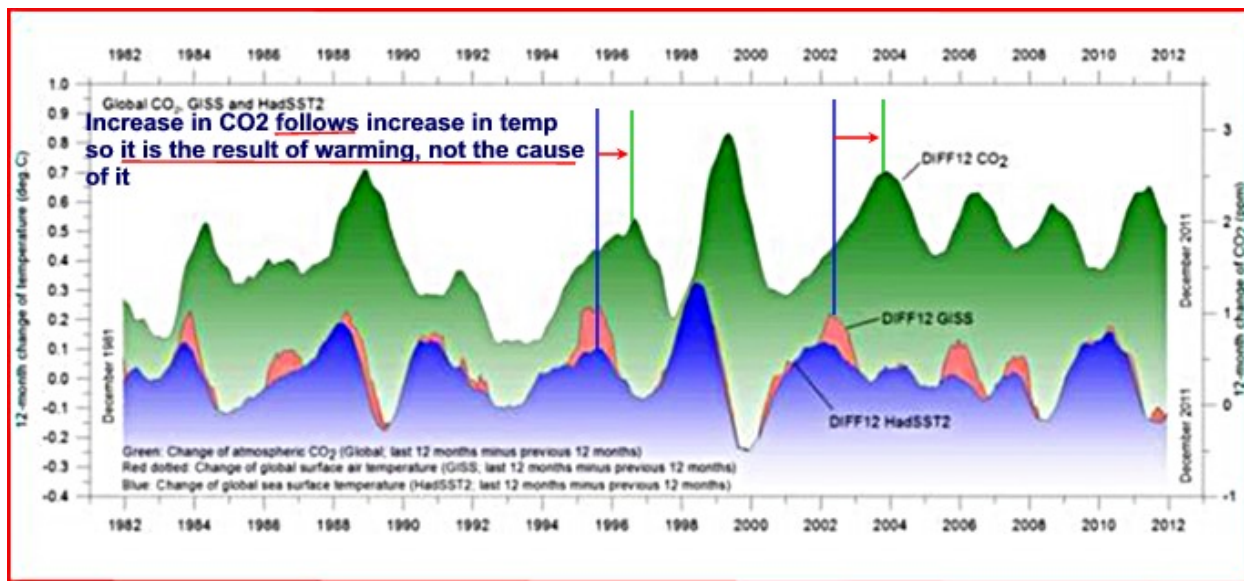


Figure 5.7.3. Lead-lag relationship of increased temperature and increased CO₂ over historic time. Adapted from Humlum, O., Stordahl, J., and Solheim, J. 2012. The phase relation between atmospheric carbon dioxide and global temperature. *Global and Planetary Change* **100**: 51–69. <http://dx.doi.org/10.1016/j.gloplacha.2012.08.008>.

Conclusion

Changes in atmospheric carbon dioxide levels lag temperature change by at least many hundred years. The studies reviewed here make it clear CO₂ cannot be the cause of the warmings seen in ice cores.

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5.8 Ice-sheet Mass Balance

5.8.1 Through Geological Time

Sixty million years ago, during the warm Paleogene period, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in the Antarctic and Greenland began during a Late Eocene cooling after c. 45 million years ago (Kennett, 1977; Barker *et al.*, 2007; Tripathi *et al.*, 2008), though it was probably

only in the latest Miocene, c. 10 My ago, that a major northern icecap started to accumulate (Bartoli *et al.*, 2005).

Thereafter, global cooling after the latest Pliocene, c. 3 million years ago, resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene. Throughout this process of high-latitude icecap growth, the precise location and size of ice masses depended upon the vicissitudes of local and global climate. Never, for any significant period of time, was a stable, global “ice mass balance” attained, as noted in a recent paper by Naish *et al.* (2009) about the Antarctic ANDRILL project.

The ANDRILL site recovered a marine glacial record for the past 5 million years from the seabed beneath the northwest part of the Ross Ice Shelf. Sedimentary deposition and nearby glacial advance and retreat since the Pliocene have proceeded in sympathy with the background Milankovitch ~40-kyr cyclic variations in insolation controlled by changes in Earth’s axial tilt (obliquity). Naish *et al.* state, “the WAIS ... periodically collapsed, resulting in a switch from grounded ice, or ice shelves, to open waters in the Ross embayment when planetary temperatures were up to ~3°C warmer than today and atmospheric CO₂ concentration was as high as ~400 ppm” in one especially significant warming episode during marine isotope stage 31 (early Pleistocene, 1.085–1.055 My ago) leading to the deposition of open ocean foraminifer-coccolith-diatom ooze at the Ross Sea drillsite. The extra warm periods during the generally warmer early Pleistocene and Pliocene were clearly not primarily controlled by changes in the air’s CO₂ concentration; moreover, the growth (and decay) of ice sheets occurs in response to pervasive climate changes of both deterministic and stochastic nature.

Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will vary in sympathy. There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation, Nor is there any scientific basis for the common, implicit assumption that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

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5.8.2 Modern Measurements

Observational data prior to the twenty-first century is for the most part not available to systematically quantify the processes of glacial mass balance. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment); and ICESat (Ice Cloud, and Land Elevation Satellite)—are in their infancy and often of doubtful accuracy, not least because of the complexity of data processing necessary to render the raw measurements into useful results. In addition, the data sets are so

short that they inevitably fail to capture the full range of climatic multidecadal variability.

The GRACE gravity satellite uses radar ranging to measure land ice, a technique requiring accurate knowledge of an appropriate Glacial Isostatic Adjustment (GIA) model. Current GIA calculations for ice sheets are confounded by, among other things, an effect that creates an erroneous conclusion of ice loss when in reality there has been an ice increase (Irvin and James, 2005; Shum *et al.*, 2008; Tegoning *et al.*, 2009; King *et al.*, 2012).

More generally, data from the GRACE satellite have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and other factors. NASA's Jet Propulsion Laboratory is seeking support for the launch of a new space platform, the Geodetic Reference Antenna in Space (GRASP) satellite, the primary mission of which would be to establish an accurate TRF.

The limitations of GRACE interpretations of ice mass balance are well illustrated by two recent papers. The first, by King *et al.* (2012), notes recent estimates of Antarctic ice-mass change cannot be reconciled with each other within the cited formal errors. They cite inadequacy in the models of glacial isostatic adjustment (GIA) as a major cause and adopt a new GIA model with better geological constraints. Applying this model to 2002–2010 GRACE data, King *et al.* estimate a continent-wide ice-mass change of -69 ± 18 Gt/yr. This is about one-third to one-half of other recently published GRACE estimates based on older GIA models (Velicogna, 2009; Chen *et al.*, 2009; Zwartz, 2009), and it represents a $+0.19 \pm 0.05$ mm/yr sea-level change.

Alternatively, Shepherd *et al.* (2012) used “an ensemble of satellite altimetry, interferometry, and gravimetry data sets using common geographical regions, time intervals, and models of surface mass balance and glacial isostatic adjustment to estimate the mass balance of Earth's polar ice sheets” over the period 1992–2011. They estimate the polar ice sheets have contributed 0.59 ± 0.20 mm/yr to the rate of global sea-level rise, driven by individual changes of mass of -142 ± 49 Gt/yr in Greenland, $+14 \pm 43$ Gt/yr in East Antarctica, -65 ± 26 in West Antarctica, and -20 ± 14 Gt/yr in the Antarctic Peninsula.

Notwithstanding the careful and systematic analysis to which the data have been subjected, the uncertainty of these estimates is manifest in the cited

error bounds, which range from about 30% to almost 300% of the data value. Further uncertainty as to the relevance of the results is implicit in Shepherd *et al.*'s own caution that “assessments of mass imbalance based on short geodetic records should be treated with care, because fluctuations in surface mass balance can be large over short time periods,” not to mention that the time period surveyed represents just one-third of the known 60-year oceanographic cycle.

Until an adequate TRF has been established, papers that use GRACE data, including recent reviews of ice-sheet mass balance like those of King *et al.* (2012) and Shepherd *et al.* (2012), must be viewed as speculative “best interpretations” of the available, noisy data. However, and noting Earth has no intrinsic or “preferred” long-term ice mass balance (as discussed in Section 5.8.1), the fact that as yet we have no way of accurately measuring ice sheet dynamics does not lessen the intrinsic interest of studying historic and modelled changes in the planetary ice budget through time.

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5.8.3 Stability of the Antarctic Ice Sheet

5.8.3.1 Geological setting

The Antarctic ice sheet came into existence a little more than 40 million years ago, during the Eocene, and its size has fluctuated according to climatic conditions. Glacial ice in the Beacon Valley near the Taylor dome of the East Antarctic Ice Sheet lies beneath sediments that contain volcanic ash dated at 8.1 million years, indicating the glacier has existed throughout the Miocene and Pliocene to the present (Sugden *et al.*, 1995). Even though global temperatures were warmer in the Miocene and Pliocene than in the Quaternary, the Antarctic ice sheet has persisted, albeit at variable extent, for tens of millions of years.

In addition to the extremely cold temperature in Antarctica, a major reason for the stability of the Antarctic ice sheet is the circumpolar vortex, a strong circulation of winds that builds up during the winter months in the upper layers of the atmosphere around Antarctica, effectively isolating the continent from the rest of the world, keeping warm ocean waters away and temperatures low. An analogous circulation system in the ocean, the cold Antarctic Circumpolar Current (ACC), keeps warm sea water away from the Antarctic coast.

As Naish *et al.* (2009) have shown (Section 5.8.1), the Antarctic ice sheet has fluctuated in volume during its evolution, even as it grew progressively through the Plio-Pleistocene to attain its current (interglacial) size. Predictions of its imminent collapse reveal a lack of understanding that isostatic sinking causes both the Greenland and Antarctic icecaps to occupy bedrock depressions; for them to “slide into the sea” would require that they “slide” uphill.

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5.8.3.2 Modern setting

Antarctica holds 91 percent of the world’s glacial ice, which is about 73 m of sea-level equivalent (Poore *et al.*, 2011), and its melting has the potential to cause major sea-level rise. Whether or not the Antarctic Ice Sheet is melting rapidly is therefore of great importance. News media carry stories nearly every week claiming the Antarctic ice sheet is melting at an accelerating rate and sea level will rise by up to 6 m in coming years. The imminent demise of the Antarctic Ice Cap was what Al Gore apparently had in mind when he warned, 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).

Ackert (2003) reported some scientists have indeed argued we are witnessing the CO₂-induced “early stages of rapid ice sheet collapse, with potential near-term impacts on the world’s coastlines.” But empirical evidence for such assertions is thin.

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5.8.3.3 Climatological reality

The average daily temperatures at the South Pole and Vostok, respectively, are -49.4°C (-57°F) and -55.1°C (-67.2°F). To melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0°C . This is not happening now, nor is it likely to happen. Claims of large-scale melting of the Antarctic ice sheet are highly exaggerated. The main Antarctic ice sheet has in fact been cooling since 1957 (see Figure 5.8.3.3.1) and ice accumulation is increasing there rather than decreasing.

The lack of a close network of weather stations in Antarctica makes interpretation of regional temperature distribution difficult. Steig *et al.* (2009) attempted to project temperatures from the West Antarctica Peninsula, where more data are available,

to the main Antarctic ice sheet and contended all of Antarctica was warming. That conclusion was hotly disputed by O'Donnell *et al.* (2010), who showed warming over the period of 1957–2006 was concentrated in the West Antarctic Peninsula and the main East Antarctic ice sheet was not warming (Figure 5.8.3.3.2).

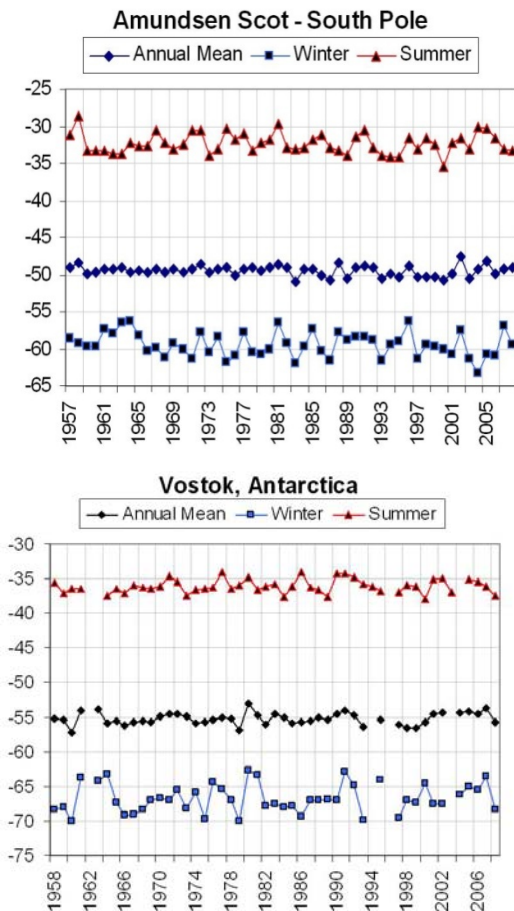


Figure 5.8.3.3.1. Temperature measurements at the South Pole (above) and Vostok (below). Note the lack of any indication of recent warming. Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

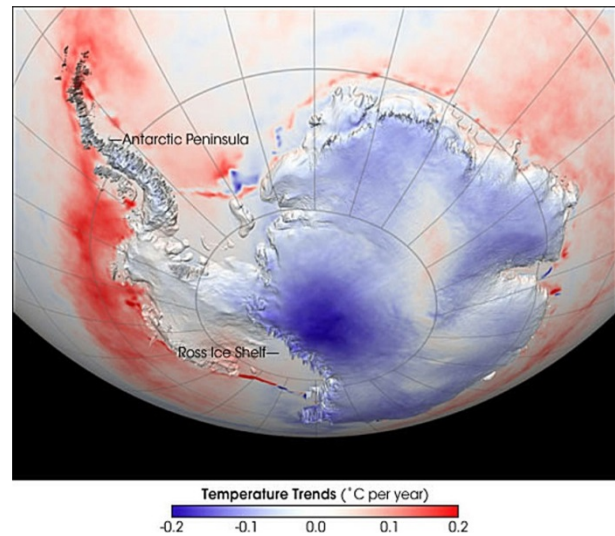


Figure 5.8.3.3.2. Rate of temperature trends in Antarctica between 1982 and 2004. Note almost all of the main East Antarctic Ice Sheet is cooling, not warming, and is not melting. The West Antarctic Peninsula is warmed by ocean currents (red). From National Oceanic and Atmospheric Administration, 2004. Antarctic temperature trend 1982–2004. <http://earthobservatory.nasa.gov/IOTD/view.php?id=6502>.

The West Antarctic Ice Sheet (WAIS) often has been 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).”

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5.8.3.4 Modelling studies and mass balance

Modelling studies have addressed how long it might take for extra warmth to bring about a collapse of the WAIS, with Pollard and DeConto (2009) concluding “the WAIS will begin to collapse when nearby ocean temperatures warm by roughly 5°C.” Huybrechts (2009) subsequently stated, “the amount of nearby ocean warming required to generate enough sub-ice-shelf melting to initiate a significant retreat of the West Antarctic ice sheet ... may well take several centuries to develop.” Once started, he concludes, the transition time for a total collapse of the West Antarctic Ice Sheet would range from “one thousand

to several thousand years.” This time period, Huybrechts notes, “is nowhere near the century timescales for West Antarctic ice-sheet decay based on simple marine ice-sheet models,” as often has been predicted in the past. Thus alarm about the short-term melting of significant volumes of the WAIS is unjustified.

Nevertheless, Gomez et al. (2010) report several studies (Oppenheimer, 1998; Meehl et al., 2007; Vaughan, 2008; Smith et al., 2009) whose authors have suggested “climate change could potentially destabilize marine ice sheets,² which would affect projections of future sea-level rise.” These studies highlight “an instability mechanism (Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007; Katz and Worster, 2010)” that “has been predicted for marine ice sheets such as the West Antarctic ice sheet that rest on reversed bed slopes, whereby ice-sheet thinning or rising sea levels leads to irreversible retreat of the grounding line.”

In contradiction of these fears, Gomez *et al.* present predictions of gravitationally self-consistent sea-level change modeled to follow grounding-line migration, derived by varying the initial ice-sheet size while considering the contribution to sea-level change that derives from various sub-regions of the simulated ice sheet. Their results “demonstrate that gravity and deformation-induced sea-level changes local to the grounding line contribute a stabilizing influence on ice sheets grounded on reversed bed slopes,” contrary to earlier assumptions. Rather than destabilizing the ice sheet, Gomez *et al.* concluded, “local sea-level change following rapid grounding-line migration will contribute a stabilizing influence on marine ice sheets, even when grounded on beds of non-negligible reversed slopes.”

Zwally and Giovinetto (2011) have provided a thorough review of the differing mass balance estimates for the Antarctic Ice Sheet (AIS) provided in earlier papers and by the IPCC. For the period 1992–2009, they report, estimates of annual mass change fall between values of +50 and -250 Gt/year. This 300 Gt/year range represents about 15 percent of the annual mass input to the AIS, and about 0.8 mm/year sea-level equivalent (SLE). They further note two estimates (+28 and -31 Gt/year) from radar altimeter measurements made by European Remote-sensing Satellites (ERS) lie in the upper part of the

² The term “marine ice sheet” appears to refer to icecaps, such as those of Greenland and Antarctica, that are surrounded by and therefore debouch into the ocean.

range, whereas estimates from the Input-minus-Output Method (IOM) and Gravity Recovery and Climate Experiment (GRACE) lie in the lower part (-40 to -246 Gt/year) of the range. By using an alternative method to process the IOM-GRACE data, Zwally and Giovinetto found “the modified IOM and a GRACE-based estimate for observations within 1992–2005 lie in a narrowed range of +27 to -40 Gt/year, which is about 3% of the annual mass input and only 0.2 mm/year SLE.”

Zwally and Giovinetto say their preferred estimate for Antarctic mass balance changes for 1992–2001 is -47 Gt/year for West Antarctica, +16 Gt/year for East Antarctica, and -31 Gt/year overall. They expressly report their results do not support the large and increasing rates of mass loss predicted in GRACE-based studies. The potential for large errors to occur in GRACE-based studies, which typically suggest overly large ice losses, has previously been stressed by Ramillien *et al.* (2006), Velicogna and Whar (2006), and Quinn and Ponte (2010). This makes it likely the Zwally and Giovinetto conclusion of a small annual Antarctic ice loss of -31 Gt/year (about 0.1 mm/yr SLE) is probably as accurate a result as it is currently possible to achieve.

Frezzotti *et al.* (2013) present a detailed analysis of the surface mass balance anomaly (SMB) for Antarctica derived from ice core data. An SMB is a step toward accomplishing a full mass balance, and it is usually defined as the difference at any location between accumulation from solid precipitation (snow) and mass loss from ablation and wind erosion. The total SMB of the grounded AIS is about 2,100 Gt/yr, with a large interannual variability up to 300 Gt/yr (Van den Broeke *et al.*, 2011).

Frezzotti *et al.* show the Antarctic SMB over the past 50 years is not unusual compared with the previous 750 years and falls well within the level of prior natural variations between <50 and >700 kg/m²/yr. They also demonstrate a good correlation exists between temporal variations in SMB and solar activity on the scale of the 200-year de Vries cycle. Beyond these studies, the preparation of the required full mass balance budget for an ice sheet requires accounting for Dynamic Ice Loss (DIL) as well as SMB; DIL, which represents the breakup and melting of the terminus of peripheral or valley outlet glaciers, is a difficult number to estimate accurately (Magand *et al.* 2007; Frezzotti *et al.*, 2007).

Boening *et al.* (2012) point out “an improved understanding of processes dominating the sensitive balance between mass loss primarily due to glacial discharge and mass gain through precipitation is

essential for determining the future behavior of the Antarctic ice sheet and its contribution to sea level rise.” They set out to assess the causes and magnitude of recent (2009–2011) extreme precipitation events along the East Antarctic coast, using data derived from CloudSat and ERA Interim reanalysis products (Dee *et al.*, 2011).

They found regional mass gain occurred mainly during May 2009 and June 2011, with most of the accumulation occurring in only a few main snowfalls driven by “prolonged changes in pressure patterns and induced poleward wind in the two years.” Over the same period, and consistent with their precipitation analysis, GRACE satellite measurements indicate an abrupt mass increase of almost 350 Gt from 2009 to 2011 in East Antarctica along the coast of Dronning Maud Land. This mass increase is equivalent to a decrease in global mean sea level at a rate of 0.32 mm/year.

Putting these results into a longer-term context, Boening *et al.* report the ERA Interim reanalysis data show no significant change in snowfall frequency or strength between 1979 and 2008. Comparing this decadal-scale stability with their finding of abrupt and episodic mass increase in 2009 and 2011, it is apparent stochastic precipitation events can affect regional mass balance in ways that significantly slow the rate of global sea-level rise.

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Earlier research

Other research regarding the stability and natural variation of the WAIS and EAIS is described and discussed in the following papers.

- Bell *et al.* (1998) used airborne geophysical data to study fast-moving ice streams on the WAIS. In conjunction with models, their data suggested a close correlation between the margins of various ice streams and the underlying configuration of sedimentary basins, which in parts appear to act as lubricants for the overlying ice. They conclude, “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,” though without indicating how such modulation might work.
- In a review of the WAIS, Bindschadler (1998) analyzed the historical retreat of its grounding line and ice front. Since the Last Glacial Maximum, the retreat of the grounding line occurred faster than its ice front, resulting in an expanding Ross Ice Shelf. Bindschadler reports “the ice front now appears to be nearly stable,” although its grounding line may be retreating at a slow rate that would cause dissipation of the WAIS in about 4,000–7,000 years time. Such a retreat, if it occurs, would sustain a sea-level rise of 0.8–1.3 mm/year. Even the slowest of these rates of sea-level rise would require a large negative mass balance for all of West Antarctica, which is not apparent in available data.
- Bindschadler and Vornberger (1998) utilized the available satellite imagery to examine changes of EAIS Ice Stream B, which flows into the Ross Ice Shelf. Since 1963, the ice stream’s width has increased by nearly 4 kilometers, at a rate an “order of magnitude faster than models have predicted.” However, the authors also report the flow speed of the ice stream decreased over this time period by about 50 percent, noting “such high rates of change in velocity greatly complicate the calculation of mass balance of the ice sheet.”
- Oppenheimer (1998) reported on 122 studies

concerned with the stability of the WAIS and its effects on global sea level. He concludes, “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.” Interestingly, however, specific studies Oppenheimer cites provide quite contrary evidence or conclusions. For example, he reports the 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” and regarding sea-ice extent “the IPCC assessment is that no trend has yet emerged.” Regarding the state and behavior of the Antarctic atmosphere and ocean, he also acknowledges “measurements are too sparse to enable the observed changes to be attributed to any such [human-induced] global warming.”

Oppenheimer concludes his review with four future scenarios for the WAIS based upon differing assumptions: (1) that the WAIS will collapse suddenly and cause a 4–6 m sea-level rise within the coming century; (2) that the WAIS will gradually disintegrate, with slow sea-level rise over the next two centuries and more rapid disintegration and sea-level rise over the following 200 years; (3) that the WAIS melts over 500–700 years, raising sea level by 6–12 mm/year; and (4) that instead of disintegrating, ice streams slow and the discharge of grounded ice decreases, leading to intra-ice sheet accretion and falling sea level. These scenarios all remain speculative, as Oppenheimer comments, “it is not possible to place high confidence in any specific prediction about the future of WAIS.”

- Wingham *et al.* (1998) studied the combined East and West Antarctic ice sheets using satellite radar altimeter measurements from 1992 to 1996 to estimate their rate of change of thickness, and using snowfall variability data from ice cores to calculate a mass balance for the Antarctic ice sheet over the past century. They conclude “a large century-scale imbalance for the Antarctic interior is unlikely,” not least because of relative sea level and geodetic evidence suggesting “the grounded ice has been in balance at the millennial scale.”
- Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of sediment cores from the eastern Weddell Sea continental shelf and nearby deep-sea floor in an attempt to track the behavior of the East and West Antarctic ice sheets. They found “significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum,” and the ice masses around the

Weddell Sea today “are more extensive than they were during the previous glacial minimum.” They conclude “the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and ... the modern West and East Antarctic ice sheets have not yet shrunk to their minimum.”

- Conway *et al.* (1999) examined the retreat of the WAIS since its maximum glacial extent 20,000 years ago. They determined the ice grounding line remained near its maximum until about 10,000 years ago, after which it retreated at a rate of about 120 meters per year, this rate also characterizing late twentieth century retreat. The researchers conclude the modern retreat of the WAIS is part of an ongoing recession underway since the early Holocene, and “it is not a consequence of anthropogenic warming or recent sea-level rise.” Extrapolating the Holocene retreat rate into the future, a complete and natural deglaciation of the WAIS will occur by about 7,000 years hence.
- Cofaigh *et al.* (2001) analyzed sediment cores from west of the Antarctic Peninsula and the Weddell and Scotia Seas for ice-rafted debris (IRD), seeking an Antarctic analogue of the Heinrich layers of the North Atlantic Ocean, which testify to the repeated collapse of the eastern Laurentide Ice Sheet and discharge of icebergs. Their search was in vain, and the rarity of IRD layers they found “argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles.”
- Pudsey and Evans (2001) studied ice-rafted debris obtained from four cores in Prince Gustav Channel, which until 1995 was covered by a floating ice shelf. Their results indicate a retreat of the ice shelf had occurred in the mid-Holocene, since when “colder conditions after about 1.9 ka allowed the ice shelf to reform.” In light of this evidence for preindustrial natural change, Pudsey and Evans were careful to state, “we should not view the recent [ice] decay as an unequivocal indicator of anthropogenic climate change.” It is likely the breakup of the Prince Gustav Channel ice shelf marks only the culmination of the Antarctic Peninsula’s natural recovery from the Little Ice Age.
- Shepherd *et al.* (2001) used satellite altimetry and interferometry to measure the rate of change of the ice thickness of the Pine Island Glacier drainage basin, WAIS, between 1992 and 1999. The grounded glacier thinned at a constant rate of 1.6 m/year, and this “thinning cannot be explained by short-term variability in accumulation and must result from

glacier dynamics.” Because glacier dynamics typically respond to phenomena operating on time scales of hundreds to thousands of years, this observation argues against twentieth century warming being a primary cause of the thinning; instead, a long-term phenomenon of considerable inertia must be at work in this particular situation.

- Hillenbrand *et al.* (2002) undertook studies of sediment cores from the Amundsen Sea, West Antarctica, a site likely to be sensitive to environmental changes related to WAIS collapse. They found all proxies sensitive to collapse changed markedly during the global climatic cycles of the past 1.8 million years, but at no level was evidence found for a Pleistocene disintegration of the WAIS. The authors remark their results “suggest relative stability rather than instability of the WAIS during the Pleistocene climatic cycles,” a conclusion “consistent with only a minor reduction of the WAIS during the last [warmer] interglacial period.” A similar conclusion was reached by Huybrechts (1990), Cuffey and Marshall (2000), and Huybrechts (2002).
- In another paper addressing possible WAIS collapse, O’Neill and Oppenheimer (2002) speculate the ice sheet “may have disintegrated in the past during periods only modestly warmer ($\sim 2^{\circ}\text{C}$ global mean) than today,” thereby claiming 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.” We are aware of no empirical evidence to support this claim.
- Raymond (2002) presents a brief appraisal of the status of the world’s major ice sheets. Relative to the WAIS, he concludes “substantial melting on the upper surface of WAIS would occur only with considerable atmospheric warming.” In a summary statement taking account of the available observations, Raymond writes “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 occur for the WAIS if the planet’s temperature should resume its post-Little Ice Age warming.
- Stone *et al.* (2003) used cosmogenic ^{10}Be exposure dates of glacially transported cobbles in elevation transects on the Ford Ranges, western Marie Byrd Land, to reconstruct a history of ice-sheet thinning over the past 10,000-plus years. They conclude “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 evidence also

suggests the maximum ice sheet stood considerably higher than this. Comparing the age of exposure with site elevation “indicates steady deglaciation since the first of these peaks emerged from the ice sheet some time before 10,400 years ago” and demonstrates the mass balance of the region has been negative throughout the Holocene. They conclude it is clear that West Antarctic deglaciation continued long after the disappearance of the Northern Hemisphere ice sheets, and may still be under way.

- Davis and Ferguson (2004) evaluated elevation changes of the Antarctic ice sheet for 1995–2000, measured by radar altimetry from the European Space Agency’s European Remote Sensing 2 satellite. They found the East Antarctic Ice Sheet had a five-year trend of 1.0 ± 0.6 cm/year, the West Antarctic Ice Sheet a five-year trend of -3.6 ± 1.0 cm/year, and the entire Antarctic continent a five-year trend of 0.4 ± 0.4 cm/year. Melting was apparent in the Pine Island, Thwaites, DeVicq, and Land glaciers of West Antarctica, which exhibited five-year trends ranging from -26 to -135 cm/year, and this was interpreted as resulting from stronger glacial flow caused by warm ocean temperatures having enhanced basal melting.
- In 2005, the journal *Climatic Change* published an editorial essay by Oppenheimer and Alley, who discussed “the degree to which warming (of the Antarctic and Greenland ice sheets) 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.” In their opinion, the key questions with respect to both ice sheets were “What processes limit ice velocity, and how much can warming affect those processes?” Commenting that no scientific consensus exists on the answers, they identify 14 areas in which our knowledge of the matter remains uncertain (Table 1), reflecting both the weakness of current models and the uncertainty in paleoclimatic reconstructions. Oppenheimer and Alley identify this list of deficiencies of knowledge as “gaping holes in our understanding.”
- 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 period 2002–2005. They conclude “the ice sheet mass decreased significantly, at a rate of 152 ± 80 km³/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea-level rise.” The mass loss came entirely from the WAIS; the East Antarctic Ice Sheet mass balance was 0 ± 56 km³/year. Velicogna and Wahr

- concede there is both ambiguity and geophysical contamination caused by signals from outside Antarctica, including continental hydrology and ocean mass variability. 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).” These estimates and adjustments are convoluted and complex, as well as highly dependent upon various models. Velicogna and Wahr acknowledge “the PGR contribution is much larger than the uncorrected GRACE trend” (by a factor of almost five), and “a significant ice mass trend does not appear until the PGR contribution is removed.” Clearly these results apply to too short a period of time, and are too model-dependent, to be useful.

- van de Berg *et al.* (2006) compared results of model-simulated Antarctic surface mass balance (SMB) and all available mass balance observations to construct “a best estimate of contemporary Antarctic SMB.” SMB data was derived from 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). The measurements included moving surficial stake arrays, location of atom bomb geochemical tracer horizons, and chemical analyses of ice cores.

van de Berg *et al.* determined “the SMB integrated over the grounded ice sheet (171 ± 3 mm per year) exceeds previous estimates by as much as 15%.” Their results differ by more than a meter per year higher in coastal areas of both East and West Antarctica.

- In another altimeter study, Wingham *et al.* (2006) utilized European remote sensing satellite measurements to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. Their measurements covered 72 percent of the area of the grounded ice sheet. After correction for isostatic rebound, these authors found the ice sheet to be growing at 5 ± 1 mm per year. This translates to the ice sheet gaining 27 ± 29 Gt of ice per year, which would lower global sea level by 0.08 mm per year.

- Ramillien *et al.* (2006) provided new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period 2002–2005, identifying a mass loss of 107 ± 23 km³/year for West Antarctica and a gain of 67 ± 28 km³/year for East

Table 1.
Summary Points from the
Oppenheimer and Alley (2005) review

Regarding the Antarctic and Greenland ice sheets, we do not know:

- i. 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.
- ii. If dynamical responses are likely to continue for centuries and propagate further inland, or if it is more likely they will be damped over time.
- iii. If surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.
- iv. If ice sheets made a significant net contribution to sea-level rise over the past several decades.
- v. What might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.
- vi. The reliability of Antarctic and Southern Ocean temperatures (and polar amplification) projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.
- vii. The prospects for expanding measurements and improving models of ice sheets, nor the timescales involved.
- viii. If current uncertainties in future ice sheet behavior can be expressed quantitatively.
- ix. What would be useful early warning signs of impending ice-sheet disintegration nor when these might be detectable.
- x. 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.
- xi. If the concept of a threshold temperature is useful.
- xii. If either ice sheet seems more vulnerable, and thus should provide a more immediate measure of climate “danger” and a more pressing target for research.
- xiii. If any of the various temperatures proposed in the literature as demarcating danger of disintegration for one or the other ice sheet is useful in contributing to a better understanding of “dangerous anthropogenic interference.”
- xiv. On what timescale future learning might yield the answers to these questions.

- Antarctica, resulting in an average net ice loss for the entire continent of 40 km³/year and a sea-level rise of 0.11 mm/year. This result 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 nine years of satellite radar altimetry data from the European Remote-sensing Satellites ERS-1 and -2. However, and as Ramillien *et al.* concede, “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) review the three principal ways by which ice sheet mass balance is estimated: by measuring the difference between mass input and output, by monitoring the changing geometry of the continent, and by modeling the dynamic and climatic evolution of the continent. The researchers conclude “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.” They also report “the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale,” which they describe in terms of centuries.
- 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). Having found a good match between the model output and observations, and after analyzing the data-driven results for trends over the period 1980–2004, the researchers report “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. They conclude “the simulated present-day surface mass balance is skilful on continental scales,” which gives them confidence regarding their mass balance projections for the end of the twenty-first century.

The projections indicate by that time “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 century and a cumulative sea-level decrease of about 6 cm. The simulated temperature increase causes increased moisture transport toward the interior of the continent where the moisture falls as snow, causing the continent’s ice sheet to grow.

Conclusions

Several arguments contradict the idea that human-caused global warming is putting Antarctica under threat of massive ice loss with attendant effects on local environments and global sea-level rise.

First, the mild warming witnessed in the late twentieth century was well within the bounds of natural variation and now has ceased: Global average temperature has not increased since at least 1996. The warming that is assumed to drive the system, and in particular all of the model studies, is no longer occurring.

Second, and even if warming were still occurring, the results of Krinner *et al.* (2007) suggest the likely regional response is enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; i.e., an increasingly positive mass balance.

Third, despite the last few interglacials being warmer than the Holocene by 2–5° C (Petit *et al.*, 1999), several studies have found sediment cores adjacent to Antarctica provide no evidence of any dramatic breakups of the WAIS over the past few glacial cycles. With or without resumed global warming, there is therefore no reason to expect changes in the Antarctic icecap other than those that happen naturally. Furthermore, we know 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 the late twentieth century, yet no evidence exists of even a partial WAIS disintegration at that time. The Antarctic ice sheet also appears to have been impervious to the effects of the climate change that characterized the Medieval Warm Period and Little Ice Age. Representing, as they do, the 1,500-yr Bond rhythm, these types of events—and specifically, a new Little Ice Age—are the most likely significant external major forcing agents that will confront Antarctica over the next 1,000 years.

Fourth, though most mass balance calculations are based upon the shifting sands of computer modeling, the evidence so far indicates West

Antarctica is warming and losing significant ice mass, and East Antarctica is cooling and accreting ice. The sum of that evidence indicates the whole Antarctic icecap is close to mass balance (Zwally and Giovenetto, 2011). As Davis and Ferguson (2004) have shown, and driven by the significantly positive trend of the much larger East Antarctic ice sheet, the ice volume of Antarctica increased over the last five years of the twentieth century, driven by increased snowfall.

Fifth, many of the most cited papers on Antarctica involve complex computer modeling and applying the GRACE gravity data and a contemporary geoid model, both of which are highly uncertain. The modeling study of Krinner *et al.* (2007) demonstrated an impressive ability to reconstruct past mass balance changes over the late twentieth century and may therefore perhaps be viewed with a little more confidence than most other similar studies. The projections of this model out to 2100, and based upon continuing warming, are for increased ice accretion across Antarctica. Thus, at least one successful model predicts CO₂-induced global warming, should it occur, will actually buffer the world against the much-hypothesized catastrophic loss of ice mass from the polar icecaps and also against the feared impact of ice-melt-driven sea-level rise.

Sixth, and finally, several studies, for example from Marie Byrd Land and in Pine Island Bay, have demonstrated a pattern of steady Holocene ice retreat that occurred at rates similar to modern retreat. The authors of these studies have concluded this retreat is simply a manifestation of the slow but steady deglaciation taking place ever since end of the last great ice age. As Ackert (2003) states, “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.” Therefore, and as Anderson and Andrews (1999) have shown, the great inertial forces at work over the millennia suggest parts of the East and West Antarctic Ice Sheets will continue to slowly wane and release icebergs to the Southern Ocean over the coming years, decades, and centuries quite independent of short-term changes in global air temperature.

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5.8.4 Stability of the Greenland Ice Sheet

The Greenland ice sheet is the second largest ice mass in the world (Figure 5.8.4.1). It is 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km². The mean altitude of the ice surface is 2,135 m, and the ice is up nearly 3 km thick in central Greenland. The lowest mean annual temperatures are about -31°C. Because the Greenland ice sheet is not a polar glacier, meltwater occurs at the base of the glacier, which facilitates basal sliding. The ice sheet margin reaches the sea only in limited areas, so no large ice shelves occur. Large outlet glaciers flow through deep fiords around the periphery of

Greenland and calve off into the ocean, producing numerous icebergs.

Many claims are made that melting of the Greenland ice sheet during the post-1977 warm period occurred at an unprecedented or extreme rate, and that in consequence damaging sea-level rise would occur. These claims seldom are tested against known climatic records. Past temperature records (Figure 5.8.4.2) show Greenland has followed a predictable pattern of multidecadal warming and cooling over the past century. Ice volume also has waxed and waned, following both global temperatures and the warming/cooling patterns in the oceans (Chylek *et al.*, 2004, 2006). Greenland's history includes two periods of cooling and two periods of warming over the past 100 years, with the warmest year being 1941 and the warmest decades being the 1930s and 1940s.

The most recent (post-1977) Arctic warming and resultant increased ice melt were not at all unusual. Kobashi *et al.* (2011) provide a longer, 2,000-year long context for these historical measurements (Figure 5.8.4.3). They reconstructed Greenland surface snow temperature variability at the GISP2 site using argon and nitrogen isotopic ratios ($\delta^{15}\text{N}$, $\delta^{40}\text{Ar}$) from air bubbles in the core, finding the average Greenland snow temperature over the past 4,000 years has been -30.7°C with a standard deviation of 1.0°C. In comparison, the current decadal average surface temperature (2001–2010) at the GISP2 site is -29.9°C. Similar results have been achieved using the borehole temperature inversion technique by Dahl-Jensen *et al.* (1998).

The reconstructed Greenland temperature from 1845 to 1993 correlates well with the 10-year running mean Summit temperature (Box *et al.*, 2009), these results confirming the reliability of the Kobashi *et al.* (2011) reconstruction. Current decadal temperatures in Greenland clearly do not exceed the envelope of natural variability over the past 4,000 years.

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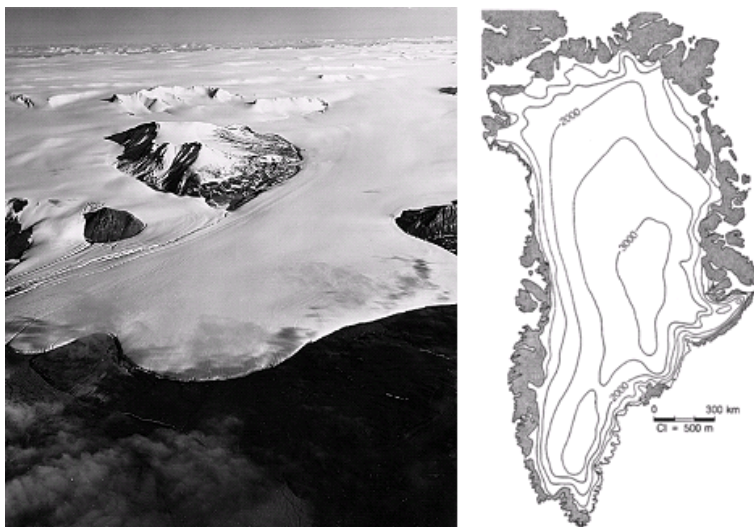


Figure 5.8.4.1. LEFT. Greenland ice sheet (Photo by Austin Post). RIGHT. Contours on the surface of the Greenland ice sheet. Adapted from Easterbrook, D.J. 1993. *Surface processes and landforms*. Prentice Hall.

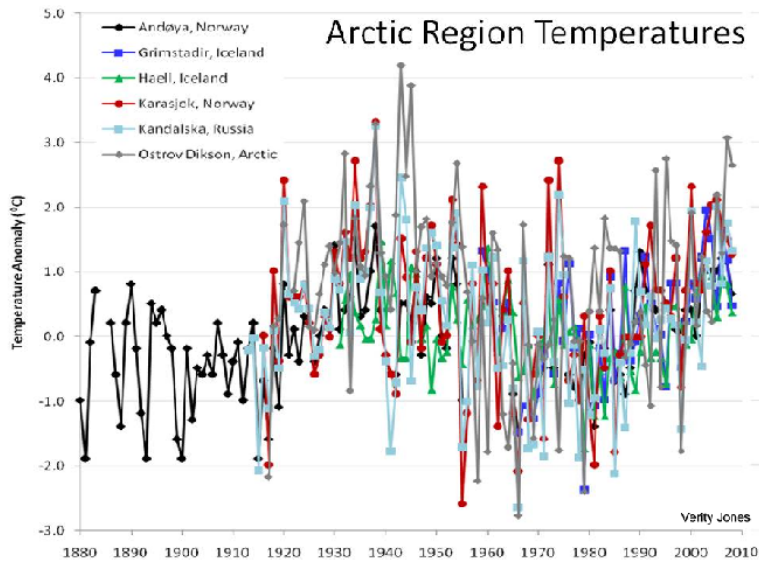


Figure 5.8.4.2. Arctic temperatures from 1880 to 2010. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221; Chylek, P., Dubey, M.K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophysical Research Letters* **33**: 10.1029/2006GL026510.

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Other research

Other recent research relevant to the mass balance of the Greenland Ice Cap includes the following papers:

- From long temperature records from southern Greenland, Godthab Nuuk on the west coast and Ammassalik on the east coast, Chylek *et al.* (2006) found “although the whole decade of 1995–2005 was relatively warm, the temperatures at Godthab Nuuk and Ammassalik were not exceptionally high,” and “almost all decades between 1915 and 1965 were warmer than, or at least as warm as, the 1995 to 2005 decade, indicating that the current warm Greenland climate is not unprecedented and that similar temperatures were the norm in the first half of the 20th century.” They note “two periods of intense warming (1995–2005 and 1920–1930) are clearly visible in the Godthab Nuuk and Ammassalik temperature records,” but “the average rate of warming was considerably higher within the 1920–1930 decade than within the 1995–2005 decade.”

Chylek *et al.* (2006) note, “An important question is to what extent can the current (1995–2005) temperature increase in Greenland coastal regions be interpreted as evidence of man-induced global warming?” They conclude, “The Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary

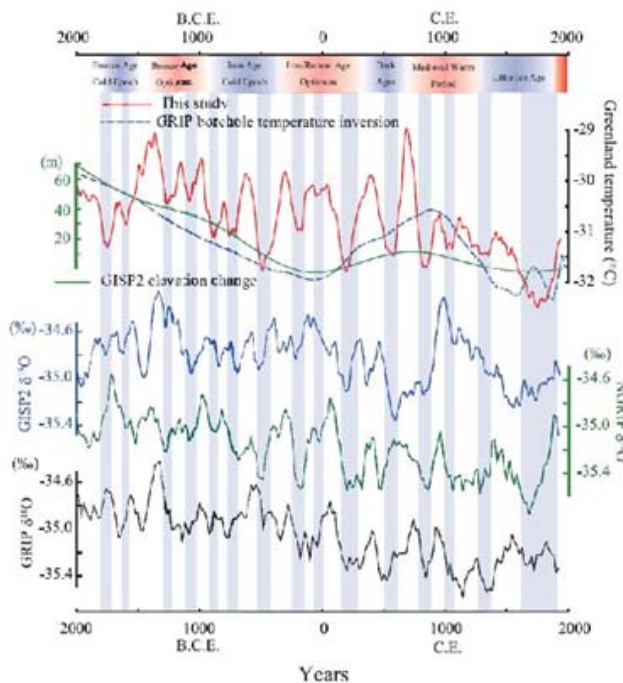


Figure 5.8.4.3. Reconstructed Greenland temperatures compared with oxygen isotope ratios (GISP2, GRIP, and NGRIP) for the past 2,000 years. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

condition for a period of warming to arise,” and “the observed 1995–2005 temperature increase seems to be within the natural variability of Greenland climate.”

- Ettema *et al.* (2009) state “to better quantify and predict the mass balance and freshwater discharge of the Greenland Ice Sheet requires improved knowledge of its surface mass balance (SMB),” defined as the annual sum of mass accumulation (snowfall, rain) and ablation (sublimation, runoff). They apply a regional atmospheric climate model over the Greenland Ice Sheet and its surrounding oceans and islands at the unprecedented high horizontal resolution of ~11 km, coupled to a physical snow model that treats surface albedo as a function of snow/firn/ice properties, meltwater percolation, retention, and refreezing. The atmospheric part of the model was forced at the lateral boundaries and the sea surface by the global model of the European Centre for Medium-Range Weather Forecasts for the period September 1957 to September 2008.

The model projected an annual precipitation for the Greenland ice sheet for 1958–2007 that was up to 24 percent higher, and a surface mass balance that was up to 63 percent higher, than previously thought. The GIS’s SMB averaged 469 ± 41 Gt/year over the study period. Before 1990, none of the mass balance components exhibited a significant trend, but after 1990 a slight downward trend of 12 ± 4 Gt/year occurred in SMB. Though lacking the context of a full mass balance for Greenland, Ettema *et al.* still felt able to conclude, “considerably more mass accumulates on the Greenland Ice Sheet than previously thought,” adjusting earlier estimates upwards by as much as 63 percent.

- Sundal *et al.* (2011) report on five years of satellite observations (1993, 1995–1998) of ice motion in southwest Greenland. As in previous studies, they found although peak ice flow speeds are positively correlated with the degree of melting, mean summer flow rates are not. This is because glacier slow-down usually occurs only when a critical run-off threshold of about 1.4 cm/day is exceeded. In the first half of summer, flow is similar in all years, but increased flow during later summer is 62 ± 16 percent less in warmer years. Accordingly, in warmer years “the period of fast ice flow is three times shorter and, overall, summer ice flow is slower.” Sundal *et al.* concluded, perhaps counterintuitively but as van de Wal *et al.* (2008) showed earlier, “a long-term (17-year) decrease in Greenland’s flow [occurred] during a period of increased melting.”

- Bjork *et al.* (2012) used data gathered by the seventh Thule Expedition (Gabel-Jorgensen, 1935, 1940), which surveyed the southeast coast of Greenland in 1932–1933, comparing the data with later aerial photographs and satellite images in order to study glacial behavior between 1932 and 2010. The terminus regions of 132 glaciers along more than 600 km of the southeast Greenland coastline were included in the study.

Two significant glacier recession events were identified, one during the 1930s (1933–1943) and another during the 2000s (2000–2010), accompanied by increasing temperatures. Marine-terminating glaciers retreated more rapidly during the recent warming, which was otherwise manifest in similar ways to the 1930s warming—in fact, “many land-terminating glaciers underwent a more rapid retreat in the 1930s than in the 2000s.” Bjork *et al.* point out the recent high rate of retreat may slow when retreating marine-terminating glaciers reach their grounding line and become less sensitive to the influence of ocean temperature (Howat *et al.*, 2008; Moon and Joughin, 2008), and positive or negative feedback mechanisms relating to the cold East Greenland Coastal Current may also come into play (Murray *et al.*, 2010).

- Bergmann *et al.* (2012) reevaluated GIS mass balance over the longer timespan of 2002–2010, using what they view as improved post-processing techniques. They found a decreasing mass loss of the GIS over the last few years for all the considered sources (UTCSR, GFZ, and JPL) and several filtering methods (Gaussian and Gaussian + ICA for averaging radii of 300, 400, and 500 km). Bergmann *et al.* report “the increase in snowfall since winter 2008–2009 in the south and since 2009–2010 in the north, and also a deceleration of the glacier discharge since 2008 reported in several studies using independent data, are responsible for the decrease in mass loss of Greenland.”

- Kjaer *et al.* (2012) used a digital elevation model derived from aerial photographs to extend the record of Dynamic Ice Loss for northwestern Greenland back to 1985. They describe two independent dynamic ice loss events, one extending from 1985 to 1993 and the other from 2005 to 2010, separated by periods of relative ice stability (“limited mass changes”). The ice mass changes were caused primarily by short-lived dynamic ice loss events rather than by changes in the surface mass balance, which, as Kjaer *et al.* point out, “challenges predictions about the future response of the Greenland Ice Sheet to increasing global temperatures.”

Conclusions

As for Antarctica, though perhaps to a lesser degree, the mass balance of the Greenland Ice Sheet (GIS) is of high interest in the context of global warming because the IPCC projects melting of the whole ice sheet would contribute nearly 7 meters to sea-level rise (Bergmann *et al.*, 2012).

Predicting the sea-level response that will occur as a result of changes in the global cryosphere requires an accurate knowledge of the present-day and recent-past mass balance for the major icecaps and glaciers throughout the world as well as a prediction of the stability through time of present-day mass balances. Prior to the availability of satellite measurements, the mass balances of the major ice sheets were poorly known.

Even today, representing these matters accurately remains a difficult task because of the variety and complexity of the processes that control the accumulation and destruction of glacial ice, and because of inadequacies in our measuring systems (Section 5.8.2 above).

The literature summarized above makes clear no empirical evidence yet exists for unusual or unnatural temperature or ice volume changes on the Greenland ice sheet.

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Earlier research

Other evidence regarding the stability and natural variation of the Greenland ice sheet is described and discussed in the following earlier research papers.

- Krabill *et al.* (2000) used 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. The region exhibited a net thickening of 5 ± 5 mm/year; but after 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. Krabill *et al.* described the net balance as “zero.”

At lower elevations, thinning predominated along approximately 70 percent of the coast. Here, however, data were so sparse (widely spaced flight lines) that the researchers acknowledged, “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.” They then interpolated between this calculated coastal thinning rate and the nearest observed elevation changes to obtain their final estimate of mass balance, a net reduction in ice volume of $51 \text{ km}^3/\text{year}$. Acknowledging the uncertainty of this result, Krabill *et al.* note changes in ice dynamics, rather than changes in temperature, were the most likely cause of the hypothetical ice sheet thinning.

- Taurisano *et al.* (2004) describe the temperature trends of the Nuuk Fjord, West Greenland, during the past century, in order to assess the local glacial dynamics. Their data show a warming trend for the first 50 years of the 1900s, followed by cooling over the second part of the twentieth century, when the average annual temperatures decreased by approximately 1.5°C . The cooling was accompanied by “a remarkable increase in the number of snowfall days (+59 days)” and affected the summer mean as well as winter temperatures but was not accompanied by any significant change in annual precipitation. Comparison with regional data led Taurisano *et al.* to conclude the Nuuk Fjord climatic history is similar to that recorded at many other stations throughout south and west Greenland (cf. Humlum, 1999; Hanna and Cappelen, 2002, 2003).
- Zwally *et al.* (2005) used satellite radar altimetry to determine the Greenland Ice Sheet is “growing inland with a small overall mass gain,” while thinning at the margins. Similarly, Johannessen *et al.* (2005) found for the 11-year period 1992–2003 the elevation-change rate below 1,500 meters was [negative] $2.0 \pm 0.9 \text{ cm/year}$, but “an increase of $6.4 \pm 0.2 \text{ cm/year}$ is found in the vast interior areas above 1500 meters.” Spatially averaged over the whole ice sheet, this results in a net increase of $5.4 \pm 0.2 \text{ cm/year}$ (~60 cm over 11 years, or ~54 cm when corrected for isostatic uplift). Zwally *et al.* conclude the GIS experienced no net loss of mass for the decade after 1992, but instead theoretically contributed a $0.03 \pm 0.01 \text{ mm/year}$ decline in sea level.
- Rignot and Kanagaratnam (2005) used satellite radar interferometry observations of Greenland to detect what they called “widespread glacier acceleration.” Calculating 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 claim “as more glaciers accelerate ... the contribution

of Greenland to sea-level rise will continue to increase.”

The problem with this conclusion is that instead of using measurements for their evaluation, Rignot and Kanagaratnam used modeled estimates by 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 different result is reached—one of near mass balance, as indicated by the work of Zwally *et al.* (2005), Johannessen *et al.* (2005), and others.

- Nick *et al.* (2009) made a comprehensive study of the outlet glaciers that occur around the margins of the Greenland Ice Sheet. They report a recent marked retreat, thinning, and acceleration of most of Greenland’s outlet glaciers south of 70°N , which, given it paralleled a temperature rise, raises concern over future sea-level rise.

To better understand this ice history, the authors developed a numerical ice-flow model to reproduce the changes in one of the largest outlet glaciers, the Helheim Glacier. The model simulations suggest ice acceleration, thinning, and retreat begin at the calving glacier terminus, and then propagate upstream through dynamic coupling along the glacier.

- Sharp and Wang (2009) used scatterometer data to map the timing of the 2000–2004 annual melt and freeze-up on three Eurasian icecaps east of Greenland: Svalbard [Norway], Novaya Zemlya [Russia], and Severnaya Zemlya [Russia]. Their five-year study was placed in context by developing regression relationships between melt season duration and annual (June + August) mean 850-hPa air temperature over each region (from NCEP-NCAR Reanalysis) that could be used to predict the annual melt duration for each year in the 1948–2005 period. The 2000–2004 pentad has the second-longest mean predicted melt duration on Novaya Zemlya (after 1950–1954), and the third longest on Svalbard (after 1950–1954 and 1970–1974) and Severnaya Zemlya (after 1950–1954 and 1955–1959), with respect to all discrete five-year periods between 1950 and 2004.
- Wake *et al.* (2009) also attempted to assess the rapidity of Greenland ice melt, using a surface mass balance model. The authors reconstructed the 1866–2005 surface mass-balance (SMB) history of the Greenland ice sheet on a $5 \times 5 \text{ km}$ grid, using a runoff-retention model based on the positive degree, which they forced with data sets of temperature and precipitation dating back to 1866. They sought to compare “the response of the ice sheet to a recent

period of warming and a similar warm period during the 1920s to examine how exceptional the recent changes are within a longer time context.”

The model outputs suggested present-day SMB changes “are not exceptional within the last 140 years,” with the SMB decline over 1995–2005 being no different from that of 1923–1933. Wake *et al.* conclude the recent and extensively monitored SMB changes (Krabill *et al.*, 2004; Luthcke *et al.*, 2006; Thomas *et al.*, 2006) “represent natural sub-decadal fluctuations in the mass balance of the ice sheet and are not necessarily the result of anthropogenic-related warming.”

- In keeping with these earlier findings, Murray *et al.* (2010) report the Greenland Ice Sheet’s annual ice discharge doubled during the 2000s, accompanied by outlet glacier thinning, accelerating, and retreating. This phase of fast discharge was followed by slowdown, for in 2006 two of the largest glaciers in the sector, Helheim and Kangerdlugssuaq, slowed down simultaneously (Howat *et al.*, 2007), ceased thinning (Stearns and Hamilton, 2007; Howat *et al.*, 2007), and even readvanced (Joughin *et al.*, 2008). Other nearby glaciers behaved in similar fashion (Howat *et al.*, 2008; Moon and Joughin, 2008), making the slowdown from 2006 widespread, synchronized throughout southeast Greenland, and lasting until at least 2008.

Conclusions

Arguments similar to those offered in discussing the impact of global warming on Antarctic ice mass-balance (Section 5.8.3 above) apply also to Greenland. However, much longer instrumental temperature records exist for Greenland than Antarctica, and these show beyond doubt that previous natural warming cycles at least equalled, and more probably exceeded, the mild warming at the end of the twentieth century.

In addition, several Greenland studies have stressed ice mass balance change often results from internal dynamics, and no simple relationship exists between glacial melt and increasing temperature. For example, in studying the Helheim and nearby glaciers, Nick *et al.* (2009) concluded their modeling showed “tidewater outlet glaciers should adjust extremely rapidly to changing boundary conditions at the calving terminus, which indicates that the recent rates of mass loss in Greenland’s outlet glaciers are a transient phenomenon, and should not be extrapolated into the future.”

Despite concerns expressed about global warming becoming increasingly intense in its effects in the

Arctic over the past two decades, conditions during the middle of the twentieth century seem to have been in this respect even more extreme than at any subsequent time, especially on the icecaps and associated glaciers studied by Sharp and Wang (2009), who concluded “the 1950–54 pentad ... experienced the longest melt season of the past 55 years on all three of the large Eurasian Arctic ice caps.”

Meanwhile, many of Greenland’s outlet glaciers debouch directly into the ocean, which makes the work of Murray *et al.* (2010) particularly pertinent. They conclude an oscillatory mechanism is at work, whereby increasing ice wastage flow causes glacial termini to push out into warmer ocean water, there melting to enhance the rate of cold water input into the East Greenland Coastal Current, thus in turn weakening its melting capacity. Murray *et al.* conclude their research suggests the presence of “a negative feedback that currently mitigates against continued very fast loss of ice from the ice sheet in a warming climate,” noting “we should expect similar speedup and slowdown events of these glaciers in the future, which will make it difficult to elucidate any underlying trend in mass loss resulting from changes in this sector of the ice sheet.”

Ettema *et al.* (2009) recently concluded “considerably more mass accumulates on the Greenland Ice Sheet than previously thought,” adjusting upwards earlier estimates by as much as 63 percent, which suggests the Northern Hemisphere’s largest ice sheet is not in imminent danger of disintegration.

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5.9 Mountain Glaciers

Over periods of decades to millennia, most valley glaciers' ice either extends in length down-valley (meaning accumulation must be exceeding melting), or shrink in size or retreat up-valley (meaning melting must be exceeding accretion).

5.9.1 Holocene glacial history

Few quantitative observations of glacier extent exist prior to about 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Glacier retreat has not been constant over the past several centuries. Instead, glaciers advanced and retreated multiple times as global climate cooled and warmed repeatedly as Earth passed through and then gradually thawed out from the Little Ice Age.

Was the most recent retreat driven by human-caused global warming? For the most part certainly not, because most of the retreat since the Little Ice Age occurred long before human-related carbon dioxide emissions reached a level where they conceivably could have been a factor. Achieving a proper perspective on the advance and retreat of

alpine glaciers therefore requires data be viewed in the context of Holocene (last 10,000 years) glacial advance and retreat.

Barclay *et al.* (2009) have provided an extensive and up-to-date review of what is known about Alaskan Holocene glacial activity and its relationship to temperature. They found the “termini of land-based valley glaciers were in retracted positions during the early to middle Holocene,” but “neoglaciation was underway in some areas by 4.5–4.0 ka and major advances of land-based termini occurred by 3.0 ka.” Most dramatic, however, were the Little Ice Age (LIA) glacial advances, which culminated in two phases in the 1540s–1710s and 1810s–1880s, of which they state, “moraines of these middle and late LIA maxima are invariably the Holocene maxima in coastal southern Alaska,” adding, “LIA advances are also recognized as major expansions in all glacierized mountain ranges in Alaska.” In addition, they state researchers have determined “Holocene fluctuations of Alaskan land-terminating glaciers have primarily been forced by multi-decadal and longer timescale changes in temperature.”

These observations suggest changes in glaciation in Alaska during the twentieth century likely started after the coldest portion of the Holocene, the Little Ice Age, when Earth cooled and then warmed again quite naturally, without any reference to rising human atmospheric CO₂ contributions.

Reference

Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* 28: 2034–2048.

Other research

Similar inferences to those from drawn from Alaska have been drawn from other summaries of Holocene glacial history worldwide, including the following.

- Rodbell *et al.* (2009) reported on Andean glaciers in South America. These authors updated “the chronology of Andean glaciation during the Lateglacial and the Holocene from the numerous articles and reviews published over the past three decades,” noting the Andes “offer an unparalleled opportunity to elucidate spatial and temporal patterns of glaciation along a continuous 68-degree meridional transect.” They found “all presently glacierized mountain ranges contain multiple moraines deposited during the last 450 years” and “these correlate with the Little Ice Age as defined in the Northern

Hemisphere.” In addition, they note most Andean regions “reveal a nearly continuous temporal distribution of moraines during the Little Ice Age.”

The occurrence of the Little Ice Age in essentially all of the glaciated portions of the Northern Hemisphere and the great meridional expanse of most of Andean South America, as well as the similar glacial activity of both parts of the planet during this time period, provide strong support for the proposition that montane glaciation began to retreat when much of the world commenced its return to its current, milder climatic state from what could be called the Holocene’s “thermal basement,” i.e., the Little Ice Age.

- In another study of Holocene glacier change, Nesje (2009) compiled, assessed, and evaluated “evidence of Late Glacial and Holocene glacier fluctuations in Scandinavia as deduced from ice-marginal features, marginal moraines, proglacial terrestrial and lacustrine sites, using especially new information that has become available since the review paper published by Karlen (1988).” Nesje reports data indicate significant late-glacial ice-sheet fluctuations and glacial contraction during the early and mid-Holocene and subsequent Neoglacial expansion, peaking during the Little Ice Age. These observations, he writes, are “in good agreement with other presently glaciated regions in the world,” as described by Solomina *et al.* (2008) and references therein.

- Other authors have confirmed the Little Ice Age in Scandinavia, as in most parts of the world where glaciers formed and grew during that period, was a depressing and dangerous time (Luckman, 1994; Villalba, 1994; Smith *et al.*, 1995; Naftz *et al.*, 1996). Alpine glaciers advanced in virtually all mountainous regions of the globe during that period, eroding large areas of land and producing masses of debris. Ice streamed down mountain slopes to carve paths through the landscape, moving rocks and destroying all vegetation in their paths (Smith and Laroque, 1995).

Continental glaciers and sea ice expanded their ranges as well during this period (Grove, 1988; Crowley and North, 1991). Near Iceland and Greenland, in fact, the expansion of sea ice during the Little Ice Age was so great it isolated the Viking colony established in Greenland during the Medieval Warm Period, leading to its eventual abandonment (Berghthorsson, 1969; Dansgaard *et al.*, 1975; Pringle, 1997).

- Another Holocene study, this time of European

glacial activity by Ivy-Ochs *et al.* (2009), presented “a summary of the evidence for suggested periods of glacier advance during the final phase of the Alpine Lateglacial and the Holocene,” interweaving “data obtained from ^{10}Be surface exposure dating, radiocarbon dating of wood and peat washed out from the presently melting glacier tongues, dendrochronological investigations on wood from the glacierized basins, tree-line studies and archaeological evidence.”

The authors found “the earliest Holocene (between 11.6 and about 10.5 ka) was still strongly affected by the cold climatic conditions of the Younger Dryas and the Preboreal oscillation,” but “at or slightly before 10.5 ka rapid shrinkage of glaciers to a size smaller than their late 20th century size reflects markedly warmer and possibly also drier climate.” After 3.3 ka, however, “climate conditions became generally colder and warm periods were brief and less frequent.” Finally, they note “glaciers in the Alps attained their Little Ice Age maximum extents in the 14th, 17th and 19th centuries, with most reaching their greatest Little Ice Age extent in the final 1850/1860 AD advance.”

Like their alpine glacier counterparts in Scandinavia, as described by Nesje (2009), glaciers of the European Alps also reached their maximum Holocene extensions close to the end of the Little Ice Age. At that time there existed the greatest potential for significant glacial retreat of the entire Holocene interglacial, for in an oscillatory climatic regime, the point of lowest temperature decline also represents the point of the greatest potential for a significant temperature increase. It would be expected, then, that the subsequent temperature recovery of Earth would be quite substantial, as there was much prior cooling to be overcome to return the planet to a climatic state more characteristic of the bulk of the Holocene.

- Considering glacial change over a shorter timeframe, Vincent *et al.* (2007) analyzed the impact of climate change over the past 100 years on high-elevation glaciated areas of the Mont Blanc range, including the ice fields that cover the Mont Blanc (4,808 m) and Dôme du Goûter (4,300 m) peaks. Surface ablation is negligible for these high-elevation areas, and the surface mass balance is mainly controlled by snow accumulation.

At Dôme du Goûter, ice fluxes were calculated through two transversal sections by two independent methods in order to assess long-term surface accumulation. A comparison between these results and recent accumulation observations, together with the strong relationship between valley precipitation

and snow accumulation, suggests surface accumulation rates did not change significantly over the entire twentieth century. Vincent *et al.* state “the most striking features ... are the small thickness changes observed over the 20th century. For both areas, thickness variations do not exceed ± 15 m. The average changes are +2.6 m at Dôme du Goûter and -0.3 m at Mont Blanc. Considering the uncertainty interval, i.e., ± 5 m, it can be concluded that no significant thickness change is detectable over most of these areas.” These findings show these high-elevation glaciated areas have not been significantly affected by climate change over the past 100 years.

- Kaser *et al.* (2010) examined the ice fields that top Mt. Kilimanjaro’s highest peak, Kibo. Kaser *et al.* write these features have garnered “particular attention” since Irion (2001) attributed modern changes in them to “increased air temperature in the context of global warming” and Thompson *et al.* (2002) reported what they described as the “near extinction of the ice on Kibo,” which they characterized as being “unprecedented over the last 11,700 years.” Kaser *et al.* (2004) developed an alternative hypothesis, namely that atmospheric moisture controls the modern-time glacier changes on Kibo, as Kaser *et al.* (2010) indicate is also suggested by the work of Molg and Hardy (2004), Cullen *et al.* (2006, 2007), and Molg *et al.* (2003, 2006, 2009a, b). This finding, in their words, “rules out rising local air temperature (i.e. on the peak of Kibo) as the main driver of observed changes during the last 120 years.”

Based on their review of all available information on present-day phenomena that control the glaciers on Kilimanjaro, Kaser *et al.* (2010) conclude “minor changes in thickness have no impact on the changing surface area of the tabular plateau glaciers,” while noting “plateau glacier area decrease has been strikingly constant over the twentieth century” and “ablation rates of the ice walls are [also] persistently constant.” In addition, their analyses suggest the mountain’s plateau ice “may have come and gone repeatedly throughout the Holocene” and the reduction of plateau ice in modern times “is controlled by the absence of sustained regional wet periods rather than changes in local air temperature on the peak of Kilimanjaro.”

Conclusions

Studies of Holocene glacial history show valley glaciers have waxed and waned worldwide for the past ten millennia. These glacial advances and retreats have occurred in sympathy with natural climate forcings. No evidence exists that unnatural glacial

retreat occurred in the late twentieth century forced by human carbon dioxide emissions.

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5.9.2 European Alpine Glaciers

European alpine glaciers provide most of the longer historical and instrumented records of fluctuations in valley glacier size. Despite a large corpus of research literature, no paper yet demonstrates any correlation between increasing atmospheric CO₂ levels and the glacial melting projected by IPCC computer models, or supports their claim that Earth has recently warmed to its highest temperature of the past thousand years.

We summarize below recent studies of European glaciers, some of which have been stable or even advancing over the past 30 years despite the mild late twentieth century warming.

Joerin *et al.* (2006) used radiocarbon dating of materials found in subglacial and proglacial sediment, together with previously published data, to construct a Holocene glacial history of the Swiss Alps over the past ten thousand years. The results demonstrate “alpine glacier recessions occurred at least 12 times during the Holocene” and, glacier retreats have decreased in frequency since 7,000 years ago, and especially since 3,200 years ago, a trend that culminated in the Little Ice Age maximum advance. Moreover, the last major glacial retreat occurred between 1,400 and 1,200 years ago, a little before the Medieval Warm Period. A similar retreat occurred in the Great Aletsch Glacier between 1,200 and 800 years ago (Holzhauser *et al.*, 2005)

Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 to compute the yearly mass balances of the Swiss Silvretta, Rhone, Aletsch, and Gries glaciers. All four glaciers have steadily, if episodically, shrunk since 1865 (Figure 5.9.2.1), with no acceleration of the shrinkage over time, which is required by the anthropogenic global warming hypothesis.

Linderholm *et al.* (2007) examined the world’s longest available mass-balance record from a mountain glacier, the Storglaciaren in northern Sweden. The record is well correlated with the records of other glaciers in the same region (Holmlund and Jansson, 1999), suggesting it is representative of northern Swedish glaciers. Figure

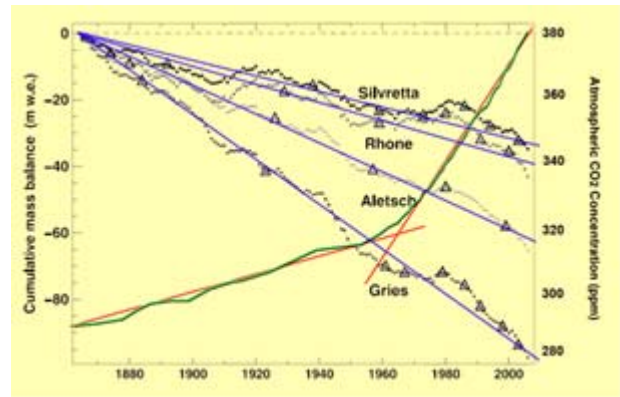


Figure 5.9.2.1. Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in the Swiss Alps to compute the yearly mass balances of four glaciers (linear trends fitted). Green line indicates atmospheric CO₂ concentrations, with two fitter linear segments (red lines). Adapted from Huss, M., Bauder, A., Funk, M., and Hock, R. 2008. Determination of the seasonal mass balance of four Alpine glaciers since 1865. *Journal of Geophysical Research* **113**: 10.1029/2007JF000803.

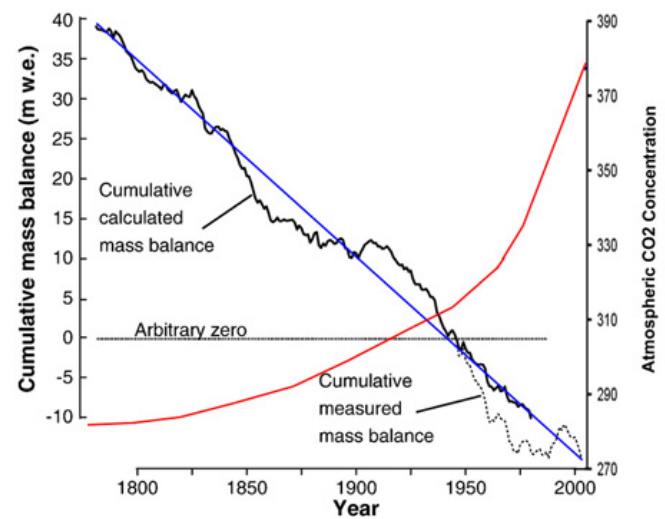


Figure 5.9.2.2. The cumulative reconstructed net mass balance history of Sweden’s Storglaciaren, to which we have added the fit-by-eye descending linear relationship (blue line), and the history of the atmosphere’s CO₂ concentration (red line). Adapted from Linderholm, H.W., Jansson, P., and Chen, D. 2007. A high-resolution reconstruction of Storglaciaren mass balance back to 1780/81 using tree-ring and circulation indices. *Quaternary Research* **67**: 12–20.

5.9.2.2 shows the Storglaciaren mass balance, plotted together with the record of atmospheric CO₂ over the same time period. It is evident the same pattern of progressive ice shrinkage seen in glaciers in the

European Alps occurs at Storglaciaren, and no acceleration of melting occurs during the time of strong CO₂ increase in the second half of the twentieth century.

D'Orefice *et al.* (2000) derived a post-Little Ice Age (LIA) history for the southernmost glacier of Europe, Ghiacciaio del Calderone. The surface area of this glacier underwent slow ice wastage from 1794 to 1884, after which a more rapid reduction in area continued to 1990, by which time the glacier had lost about half its LIA surface area.

Other European glaciers show a different pattern and have not experienced consistent, progressive loss of mass. For example, glaciers in the Central Swiss Alps experienced two periods of advance, around 1920 and 1980 (Hormes *et al.*, 2001). Braithwaite (2002) reported for the period 1980–1995 “Scandinavian glaciers [have been] growing, and glaciers in the Caucasus are close to equilibrium”; and Braithwaite and Zhang (2000) reported a significant upward trend in the mass balance of Sweden’s Storglaciaren over the past 30–40 years. Additional evidence for post-LIA glacial expansion is provided by the Solheimajokull outlet glacier, southern coast of Iceland. Mackintosh *et al.* (2002) report a post-LIA minimum of 13.8 km length for this glacier in 1970, which thereafter expanded to 14.3 km by 1995. The minimum length of 13.8 km observed in 1970 also did not eclipse an earlier 300-year minimum length of 13.2 km which occurred in 1783.

Recent glacial advances also have occurred in Norway. Chinn *et al.* (2005) report glacial recession was most strongly expressed there in the middle of the twentieth century during the 1915 to 1945 warm period, 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 during the 1945 to 1977 cool period, accelerating in the late 1980s. Around 2000, some of the glacial advance began to slow, though “most of the larger outlets with longer reaction times are continuing to advance.” Chinn *et al.* report “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.” Much the same changes have occurred since 1988 “at all [western] maritime glaciers in both southern and northern Norway.”

Conclusions

The studies summarized above show no European-wide correlation exists between increasing atmospheric CO₂ levels and simple glacial melting. Instead, European glaciers display an episodic history, with phases of both retreat and advance throughout the Holocene and over the past quarter-century. During the period over which the IPCC claims Earth has warmed to its highest temperature of the past thousand years, some glaciers advanced, others retreated, and others remained essentially stable.

The histories of glaciers such as the Storglaciaren, which display cumulative post-Little Ice Age retreats, provide no compelling evidence that the retreat had anything to do with the air’s CO₂ content, not least because retreat commenced long before significant levels of industrial emissions had built up. As much to the point, a glacier like the Great Aletsch Glacier attained a length in AD 1000 only slightly less than its length today—despite there having been fully 100 ppm less CO₂ in the air then than there is today.

It is clear the ice-loss history of European glaciers was not influenced by the increase in the rate-of-rise of the air’s CO₂ content that occurred between 1950 and 1970; their rate of shrinkage also was not materially increased by what the IPCC calls the unprecedented warming of the past few decades.

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5.9.3 Asia: Himalayan Glacier History

Concern about melting Himalayan glaciers has been led by the IPCC. Alarmist assertions have included claims that almost all Indian glaciers, including the Gangotri Glacier, will vanish from Earth in the next few decades, accompanied first by flooding and then by the drying of glacial-fed rivers, desertification, sea-level rise, submergence of coastal areas, spread of diseases, and a drop in the production of food grains—all, of course, as a result of anthropogenic global warming. Early in 2011 it was discovered the IPCC’s key reference for such alarmist claims was an unrefereed report published by an environmentalist lobby group.

Meanwhile, Bali *et al.* (2011) carried out a comprehensive review of Himalayan glaciers, noting the Geological Survey of India has identified more than 9,000 valley glaciers in India and at least 2,000 more in Nepal and Bhutan (Raina, 2006), few of which are instrumented to modern standards. Hewitt (2010), investigating glaciers in the Karakoram, comments, “emerging evidence suggests that alarmist reports about the Himalaya are, at best, exaggerated,” as also pointed out by Raina (2009) and Armstrong (2010). There is strong evidence for anomalous post-Little Ice Age glacier expansion in parts of the Karakoram, nourished not only by snowfall but also by avalanche contributions.

Hewitt (2005, 2011) found Karakoram glaciers have declined by only 5 percent or so since the early twentieth century, mainly between the 1920s and

1960s. Ice loss slowed in the 1970s (Mayewski and Jenschke, 1979) during the 1945–1977 cool period, when some glaciers underwent modest advances (Kotlyakov, 1997), and modest retreat then prevailed again from the mid-1980s through the 1990s warm period. Most recently, “since the late 1990s we have reports of glaciers stabilizing and, in the high Karakoram, advancing (Hewitt, 2005; Immerzeel *et al.*, 2009),” while “total snow cover has been increasing in the high Karakoram (Naz *et al.*, 2009).”

Such a glacial history cannot have been driven simply by increasing anthropogenic carbon dioxide emissions, but rather must reflect the complex interaction of the several major processes that control glacier dynamics. In the high Himalaya, Hewitt points out, the extent and sustained high elevations of the main Karakoram, together with the “all-year accumulation regime, help to buffer glaciers against ‘warming,’” should it start to occur again. He also notes “various investigations report cooler summers recently and greater summer cloudiness and snow cover (Fowler and Archer, 2006; Naz *et al.*, 2009; Scherler *et al.*, 2011), which potentially should lead to reduced average ablation rates or numbers of ‘ablation days.’”

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Other research

Other evidence regarding the stability and natural variation of Himalayan glaciers, especially those in the western Karakoram Ranges, is further described and discussed in the following research papers.

- Schmidt and Nusser (2009) used a multitemporal/multiscale approach to studying glacial change in the Nanga Parbat region, Northern Pakistan, using historical data, repeat photography, and satellite imagery to develop a 70-year history of the behavior of that region's Raikot Glacier. They found only "relatively small rates of recession and surface changes over the last seven decades," noting "some well-defined large boulders remain in the same position in 2006 as in 1934," which indicates a high stability for the proglacial area and lateral moraines. In these respects, the Raikot Glacier is similar to "most debris-covered glaciers in the northwest Himalaya and in the nearby Karakoram, Hindu Kush and Kun Lun ranges, Raikot Glacier [which] show only minor retreating rates since the 1980s." Schmidt and Nusser report "glacier fluctuations over the past 70 years are characterized by retreat between the 1930s and 1950s, a marked advance between the 1950s and 1980s, and a relatively stable situation after 1992," but with no general trend of reducing ice mass since the 1930s.

- Chaujar (2009) used lichenometric dating of loop moraines on the Chorabari Glacier, Garhwal Himalayas to establish its history during and after the

Little Ice Age. Noting his results are consistent with "research on various glaciers of the northern and southern hemisphere [which] has shown that most of them started their retreat in the mid-18th century, thereby indicating the end of the Little Ice Age maximum," he suggests this pattern of deglaciation may be a global phenomenon.

- Copland *et al.* (2011) used a combination of previously published literature and repeat satellite imagery to catalog ice behavior in the Karakoram since 1961. They found "there has been a marked increase in the recent occurrence of glacier surging in the Karakoram" associated with "a significant increase in winter, summer, and annual precipitation in the Karakoram over the period 1961–1999." In particular, there has been "a doubling in the number of new surges in the 14 years after 1990 (26 surges) than in the 14 years before 1990 (13 surges)." This increase in glacier surging correlates with the positive mass balances reported for the Karakoram by Gardelle *et al.* (2011) and others over the past few decades and is consistent with the many other glaciological indicators of recent ice stability or expansion in this area reported by Hewitt (2005), Pecci and Smiraglia (2000), Mayer *et al.* (2006), and Quincey *et al.* (2009).

- In their review of glacial activity in the Garhwal Himalaya, Bali *et al.* (2011) report the Gangotri Glacier, which was earlier receding at a rate of around 26 m/year between 1935 and 1971 (Raina, 2003; Sharma and Owen, 1996; Naithani *et al.*, 2001; Srivastava, 2003), has more recently shown a gradual decline in rate of recession, falling to 17 m/year for 1974–2004 and 12 m/year for 2004–2005 (Kumar *et al.*, 2008). The Dokriana Glacier maintained an overall constant rate of recession (around 16–18 m/year) between the years 1962 and 1995 (Dobhal *et al.*, 2004). The recession of the Pindari Glacier diminished from about 26 m/year for 1845–1906 to about 6.5 m/year in 1966–2007 (Bali *et al.*, 2009), and the Milam Glacier has exhibited a steady rate of recession of around 16.5 m/year over the past 150 years (Shukla and Siddiqui, 2001). The terminus of the Donagiri Glacier has exhibited intermittent recession and advance (Srivastava and Swaroop, 2001; Swaroop *et al.*, 2001), and the Satopanth Glacier, which earlier had been receding at the rate of 22.86 m/year, showed a recession rate of 6.5 m/year during 2005–2006 (Ganjoo and Koul, 2009). Most conspicuously, the 70-km-long Siachin glacier "has been standing steady for the last several decades," exhibiting an almost stable terminus that receded by only 8–10 m in 1995–2008 (Ganjoo and Koul, 2009)

and showing signs of advancement during the last decade (Sinha and Shah, 2008).

- Azam *et al.* (2012) describe recent glaciological changes in the western Himalaya using mass balance and surface ice flow velocity measurements made in 2002–2010 on the Chhota Shigri Glacier in the Pir Panjal Range, which they compare with similar data collected in 1987–1989. They find “the glacier has experienced a period of near-zero or slightly positive mass balance in the 1990s ... [before] ... starting to shrink at the beginning of the 21st century,” with only a small change in position of the terminus between 1988 and 2010.

Noting the Chhota Shigri seems to be representative of other glaciers in the Pir Panjal range (Berthier *et al.*, 2007), Azam *et al.* conclude many Western Himalayan glaciers may have experienced growth rather than shrinkage during the last 10–12 years of the twentieth century. The authors note “this result challenges the generally accepted idea that glaciers in the Western Himalaya have been shrinking rapidly for the last few decades” as, for example, implied by Solomon *et al.* (2012) in the IPCC’s *Fourth Assessment Report*.

- Hewitt (2005) noted the west end of the Himalayan arc, where China, India, and Pakistan meet, was characterized by a recent anomalous gain of mass by Karakoram glaciers. This feature was referred to in subsequent studies by Zemp *et al.* (2009), Cogley (2011), and Scherler *et al.* (2011), becoming known as the “Karakoram anomaly.”

Noting the paucity of data on the Karakoram, Gardelle *et al.* (2012) set out to calculate a regional mass balance for glaciers in the central Karakoram for 1999–2008 based on differences between two sets of digital elevation data, one from the February 2000 Shuttle Radar Topographic Mission (SRTM) and the other from the December 2008 optical stereo imagery acquired by the Satellite Pour l’Observation de la Terre (SPOT5) program. Gardelle *et al.* (2012) report the presence of “a highly heterogeneous spatial pattern of changes in glacier elevation, which shows that ice thinning and ablation at high rates can occur on debris-covered glacier tongues,” and which results in “the regional mass balance [being] just positive at $+0.11 \pm 0.22$ m/year water equivalent.” Glacier expansion or speed-up consistent with this result has been previously reported by Hewitt (2005), Quincey *et al.* (2009), and Heid and Kaab (2011).

- In other research, “more than 50% of Karakoram glaciers were advancing or stable between 2000 and 2008” (Scherler *et al.*, 2011), and Fuita and Nuimura

(2011) reported a descending trend in the modeled equilibrium-line altitude in the Karakoram during 1976–1995. Fowler and Archer (2006) reported an increase in winter precipitation since 1961, a potential source for greater accumulation in the upper parts of glaciers (Hewitt, 2005; Quincey *et al.* 2009, 2011). Between 1961 and 2000, Fowler and Archer report, mean summer temperature declined at all climate stations in the region, probably resulting in a decreasing glacier melt.

Conclusions

In its *Fourth Assessment Report*, the IPCC wrote the likelihood of India’s western Himalayan glaciers “disappearing by the year 2035 or perhaps sooner is very high if the Earth keeps warming at the current rate” (Solomon *et al.*, 2007). Given the obvious importance of the Himalayan glaciers as water sources for the populous downstream lowlands of south Asia, this was an alarming scenario to promulgate, and Cogley *et al.* (2010) give an account of how this misinformation came to be adopted.

Shroder *et al.* (2000) had discovered an absence of rapid Himalayan melting some time before, during their fieldwork in 1993–1995, from which they state “the glacial fed rivers are thus not going to die an immediate death.” They pointed out “even if a time comes that there are no glaciers around, the rivers will still flow” because at the foothills the contribution of glacial melt water is only 10 to 15 percent of the total, the rest being supplied by rain and ground water.

Real-world empirical data are needed to test alarmist speculations about the disappearance of Himalayan glaciers. Byers (2007), Zemp and Haeberli (2007), and Kumar *et al.* (2008) all point out the Himalayan glacier response to climate change is poorly known, mainly because of the lack of long-term and continuous records of glacial fluctuations at sites throughout the mountain chain.

The research studies summarized above are beginning to provide the factual data required to improve our understanding of how Himalayan glaciers might respond to climate change. The beliefs of Solomon *et al.* (2007) are now more open to observational testing, and we no longer have to rely on speculative computer modeling projections.

Two main lines of empirical argument bear on the issue. The first, after Chaujar (2009), is based upon viewing twentieth century glacial change in the context of the post-LIA climatic warming that started in the 1860s and caused glacier shrinkages around the world, including in the Himalayas. As Chaujar notes, these changes started “long before the historical

increase in the air's CO₂ content could have been involved in the process of their retreat.” Hence, there is no reason to believe the late twentieth century warming, and glacial shrinkage where it occurred, were anything more than a continuation of the nonanthropogenic return of Earth from the frigid depths of the Little Ice Age.

The second argument is based on the growing number of local and regional studies becoming available from throughout the Himalayas. Though variability in ice-mass change exists from place to place, most recent studies have found the glaciers of the Indian subcontinent “are receding at a much slower pace in comparison to what they were about a few decades back” (Bali *et al.*, 2011; see also Yadav, *et al.*, 2004), or even growing in places in the Karakoram, Hindu Kush, and Western Himalayan ranges. This glacial growth appears to be driven “by a quirk of the atmospheric general circulation that is not understood”; “more snow is being delivered to the mountain range at present, and less heat” (Cogley, 2012). Gardelle *et al.* (2012) have provided strong evidence for the existence of an increasing ice mass balance in the Karakoram region, and Copland *et al.* (2011) stress that contrary to what is often claimed about many of Earth's mountain glaciers, “it is evident that glacier surging is more extensive than previously reported in the Karakoram and that the number of glacier surges has increased recently,” driven by positive mass balances.

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5.9.4 African Glaciers

African montane glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights; i.e. on large mountains. One of these, Kenya's Mt. Kilimanjaro, has achieved iconic status because of Ernest Hemingway's famous short story "The Snows of Kilimanjaro."

During the 1980s and 1990s, U.S. politicians Al Gore, John McCain, and Hilary Clinton, together with other public figures around the world, made emotional statements in support of reducing human-related CO₂, based on their (incorrect) understanding that Kilimanjaro's summit ice field was melting under the influence of anthropogenic global warming. Acknowledging subsequent research, Justice Michael Burton in his 2007 U.K. High Court judgement against Mr. Gore's film, *An Inconvenient Truth*, concluded such views are in error. Modern glacier recession on Kilimanjaro began around 1880, which rules out post-1950 human emissions as the primary cause, despite that belief being encouraged by scattered scientific reports (Alverson *et al.*, 2001; Irion, 2001; Thompson *et al.*, 2002). This oversimplified view is wrong, as shown in the following papers.

- Molg *et al.* (2003a) note all three glacier-bearing volcanic mountains in East Africa—Kilimanjaro (Tanzania, Kenya), Mount Kenya (Kenya), and Rwenzori (Zaire, Uganda)—have experienced strong

ice field recession over the past century or so. They also report, after Hastenrath (2001), “there is no evidence of a sudden change in temperature [in East Africa] at the end of the 19th century,” as confirmed by King’uyu *et al.* (2000) and Hay *et al.* (2002), who show East African twentieth century temperature records show diverse trends and do not exhibit a uniform warming signal.

- Georges and Kaser (2002) report on an automatic weather station installed in 2002 on a horizontal glacier surface at the Kilimanjaro Northern Icefield. Since then, monthly mean air temperatures have varied only slightly around the annual mean of -7.1°C , and air temperatures have never risen above freezing. It is difficult to understand how ice could melt under such conditions.
- Molg and Hardy (2004) used data from this weather station to derive an energy balance for the Kibo summit icefield on Mt. Kilimanjaro. They discovered “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 “modern glacier retreat on Kilimanjaro and in East Africa in general [was] initiated by a drastic reduction in precipitation at the end of the 19th century (Hastenrath, 1984, 2001; Kaser *et al.*, 2004),” and reduced accumulation and increased ablation have “maintained the retreat until the present (Molg *et al.*, 2003a).”
- Molg *et al.* (2003b) applied a radiation model to an idealized representation of the 1880 icecap of Kilimanjaro, concluding “modern glacier retreat on Kilimanjaro is much more complex than simply attributable to ‘global warming only.’” Instead, and as reported by many other authors, the ice retreat has been “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.”
- Cullen *et al.* (2006) report “all ice bodies on Kilimanjaro have retreated drastically between 1912–

2003,” but they add 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 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 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 report the “vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in 20th 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 their rapid recession in the first part of the twentieth century shows they “were drastically out of equilibrium,” which they take as evidence the glaciers “were responding to a large prior shift in climate.” In addition, they report “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 their continuing but decelerating demise could be helped along by the continuous slow decline in the air’s specific humidity. Cullen *et al.* confidently conclude the glaciers of Kilimanjaro “are merely remnants of a past climate rather than sensitive indicators of 20th century climate change.”

- Two additional studies, by Mote and Kaser (2007) and Duane *et al.* (2008), reject the temperature-induced decline hypothesis for Kilimanjaro. Duane *et al.* conclude “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 report “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.”
- What, then, caused the ice fields of Kilimanjaro to recede 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.* (2003a, b) say “all data indicate that modern East African climate experienced an abrupt and marked drop in air humidity around 1880,” and 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 demonstrated for the region by Kruss (1983) and Hastenrath (1984). In addition, they note “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).”

- Kaser *et al.* (2004) conclude all relevant “observations and facts” clearly indicate “climatological processes other than air temperature control the ice recession in a direct manner” on Kilimanjaro, and “positive air temperatures have not contributed to the recession process on the summit.” Those conclusions directly contradict Irion (2002) and Thompson *et al.* (2002), who see the recession of Kilimanjaro’s glaciers as a direct consequence solely of increased air temperature.

Conclusions

In support of the findings of Molg *et al.* (2003a, b), for Africa, analyses of glacier retreat throughout the tropics uniformly suggest that changes in air humidity have been dominant in controlling modern retreat where it has occurred [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)].

Kaser *et al.* (2004) conclude “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).” Regarding East African montane glaciers, it is important to remember “the dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser

and Nogler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Molg *et al.*, 2003b).” These factors are related to a drying of the regional atmosphere that commenced around 1880 and lasted through the twentieth century.

We conclude warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

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5.9.5 South America

Studies of alpine glaciers from South America fail to provide evidence for widespread or uniform glacial retreat under the influence of modern global warming.

- 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. These glaciers, together with four others on the western side of the ice field, began to retreat from their Little Ice Age maximum positions between 1850 and 1880. The trend of retreat 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,” as also has been observed at many Northern Hemisphere sites.

- Glasser *et al.* (2004) describe glacial fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte and the Hielo Patagonico Sur. The evidence indicates glacial advance and retreat since about 6,000 ¹⁴C years BP in concert with the known Roman Warm Period, cold Dark Ages, warm Medieval Warm Period, cold Little Ice Age and twentieth century warming. A similar pattern of glacial activity occurred to the east of the Hielo Patagonico Sur, in the Rio Guanaco region of the Precordillera. Here, Wenzens (1999) detected five distinct periods of glacial advancement: “4500–4200, 3600–3300, 2300–2000, 1300–1000 ¹⁴C years BP and AD 1600–1850.” The glacial advancements during

the cold interval prior to the Roman Warm Period constitute “part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al.*, 1998; Wasson and Claussen, 2002). This period coincided with the abrupt decrease in solar activity that led van Geel *et al.* (2000) to stress the importance of solar irradiance as a driver for climate variation.

Glacial histories similar to those of Patagonia have been described from geomorphological moraine analysis recorded from other parts of southern Chile (e.g., Kuylensstierna *et al.*, 1996; Koch and Kilian, 2001), the Peruvian Cordillera Blanca (Kaser and Georges, 1997), and the Bolivian Cordillera Real (Francou *et al.*, 2003). Further afield, similar histories are also known from areas peripheral to the North Atlantic and in central Asia (cf. Grove, 1988; Savoskul, 1997).

- Georges (2004) constructed a twentieth century history of glacial fluctuations in the Cordillera Blanca of Peru, the largest glaciated area in the tropics. Glacier recession of unknown extent occurred early in the century, followed by a marked readvance in the 1920s that nearly reached the Little Ice Age maximum. Thereafter came a very strong glacial mass shrinkage in the 1930s–1940s, quiescence, and an intermediate retreat from the mid-1970s until the end of the century. Georges comments, “the intensity of the 1930s–1940s retreat was more pronounced than that of the one at the end of the century,” the data indicating the rate of wastage in the 1930s–1940s was twice as great as that of the last two decades of the twentieth century. The advances in the Cordillera Blanca in the late 1920s were almost as great as those experienced there during the Little Ice Age.
- Koch and Kilian (2005) used dendrochronology to map and date the moraine systems of Glaciar Lengua and neighboring glaciers of Gran Campo Nevado in the southernmost Andes of Chile. They found the culmination of the Little Ice Age glacial advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Rothlisberger, 1986; Aniya, 1996), but 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).
- Polissar *et al.* (2006) used two 1,500-yr-long sediment cores from Lakes Mucubaji and Blanca, Venezuela, to reconstruct proxy records for glacier activity, temperature, and moisture balance in that part of the tropical Andes (the Cordillera de Merida). Techniques used included measurement for biogenic

silica, magnetic susceptibility, total organic carbon (TOC), total nitrogen (TN), $\delta^{13}\text{C}_{\text{TOC}}$, $\delta^{15}\text{N}_{\text{TN}}$, and C/N.

Polissar *et al.* note the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and $\delta^{14}\text{C}$ measurements; spectral analysis identifies significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, which match the de Vries and Gleissberg oscillations known from solar irradiance reconstructions; and the magnetic susceptibility record follows the solar-irradiance reconstruction during 1520–1650 but is not correlated with solar and volcanic forcings during that time. The four glacial advances that occurred between AD 1250 and 1810 coincide with solar-activity minima and also with temperature declines of $-3.2 \pm 1.4^\circ\text{C}$ and precipitation increases of $\sim+20\%$.

Conclusions

These South American studies make clear the strong correlation between glacial advance and retreat and the warmings and coolings of the past several centuries. Moreover, independent evidence for solar control, including at the shorter de Vries (~ 208 yr) and Gleissberg (~ 80 yr) wavelengths, is provided by Polissar *et al.*'s work in Venezuela.

Most of the observed glacial cycles date from long before a time when human CO_2 emissions could have been a cause. In addition, CO_2 levels lower than those of the twentieth century occurred during older warm intervals, and no unusual glacial retreats occurred during the mild twentieth century warming.

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5.9.6 North America

The history of North American glacial activity fails to support the claim that anthropogenic CO₂ emissions are causing glaciers to melt. Relevant studies include the following.

- 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 “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 conclude “there is no compelling indication of increasingly negative balance conditions which might, a priori, be expected from anthropogenically induced global warming.”
- Calkin *et al.* (2001) reviewed current research on Holocene neoglaciations along the Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where several periods of glacial advance and retreat have occurred during the past 7,000 years. Over the younger part of this record, a general glacial retreat occurred during the Medieval Warm Period prior to AD 1200, after which three major advances occurred during the Little Ice Age: in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century. During these three cold intervals, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers also “reached their Holocene maximum extensions.”
- 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 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.

These data provided copious evidence for the occurrence of a glacial advance that began about 3,000 years ago and probably lasted for several hundred years—equivalent to the unnamed cold period prior to the Roman Warm Period that is also known from South America. Evidence also was present for a second phase of glacial activity beginning about 1,300 years ago and which could equate with the Dark Ages Cold Period. A third, and the most extensive and recent, neoglacial interval began shortly after the Medieval Warm Period at about AD 1200 and ended in the late 1800s. Clague *et al.* comment “glaciers achieved their greatest extent of the past 3,000 years and probably the last 10,000 years” during this Little Ice Age period.

- 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).

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

Wiles *et al.* 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. 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, “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 “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.”

- Easterbrook (2010, 2011) described Holocene glacial advances and retreats on Mt. Baker in the North Cascade Range (Washington) that correlate well with the climate changes documented in the Greenland GISP2 ice core and the global temperature curve. Ice margins of Mt. Baker glaciers are shown on air photos dating back to 1943 (see Figure 5.9.6.1) (Easterbrook, 2010, 2011; Harper, 1993). Glaciers that had been retreating since at least the 1920s advanced during the 1947–1977 cool period to positions down-valley from their 1943 termini. They began to retreat once again at the start of the 1977–2007 warm period, and recent termini of the Easton and Boulder glaciers are about 450 m up-valley from

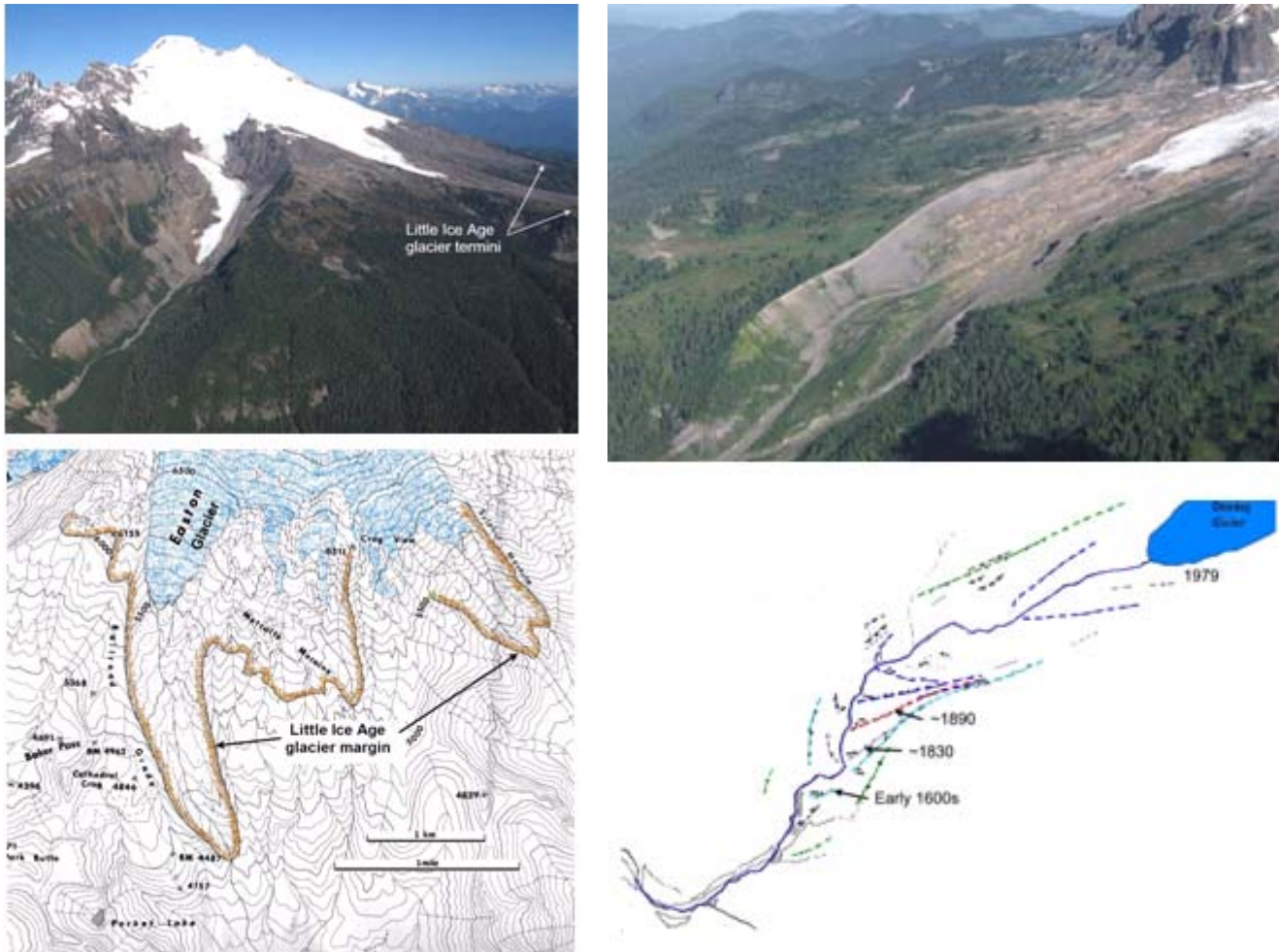


Figure 5.9.6.1. LEFT COLUMN: Photo (upper) and topographic map (lower) of ice retreat from the Little Ice Age maximum, Deming and Easton glaciers, Mt. Baker Washington. RIGHT COLUMN: Photo (upper) and sketch map (lower) of dated moraines down-valley from the Deming glacier on Mt. Baker, Washington. All adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future*. Elsevier, pp. 3–51.

their 1979 positions. These glacial fluctuations closely follow the global temperature record and indicate the warming and cooling cycles seen in the glacial record mimic global climate change. Thus, prehistoric glacial fluctuations also record global climate change.

The glaciers on Mt. Baker show a regular pattern of advance and retreat that matches sea surface temperatures in the nearby northeast Pacific Ocean (the Pacific Decadal Oscillation) (Figure 5.9.6.2), showing the glacier fluctuations occur in parallel with changes in sea surface temperature. Because the glacial record extends back many centuries, it can be used as a proxy for climate change (Figure 5.9.6.3).

- Munroe *et al.* (2012) provide a lacustrine-based Neoglacial record for the glaciers of Montana's

Glacier National Park (GNP), where a reduction in the area of glaciers in excess of 36 percent since approximately 1850 has been reported (Key *et al.*, 2002). Munroe *et al.* used analyses of the sedimentary cores for properties sensitive to the extent and activity of upstream glacier ice, including water, organic matter, carbonate, and biogenic silica content; bulk density; mass accumulation rate; phosphorus fractionation; magnetic susceptibility; L*a*b* color values; and grain size distributions.

Munroe *et al.* report all but one of their records contain evidence for glacier advances during the last millennium, corresponding with the Little Ice Age, which they describe as “the most extensive event” of the entire Neoglacial and is “strongly expressed globally—Davis *et al.* (2009).” They found the Little

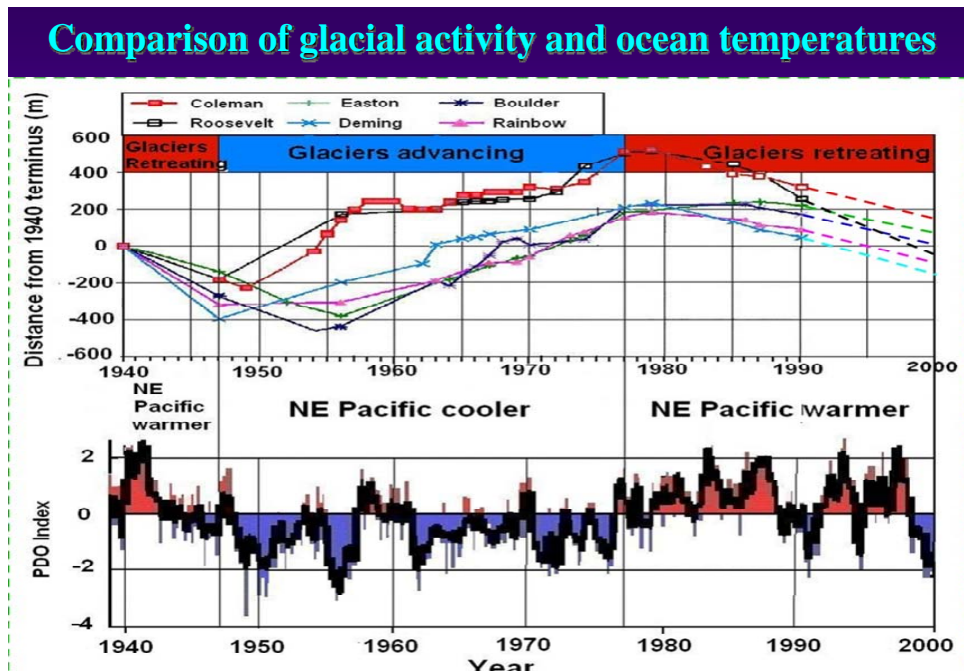


Figure 5.9.6.2. Comparison of advance and retreat of glaciers on Mt. Baker, Washington, with the Pacific Decadal Oscillation. Adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future.* Elsevier, pp. 3–51.

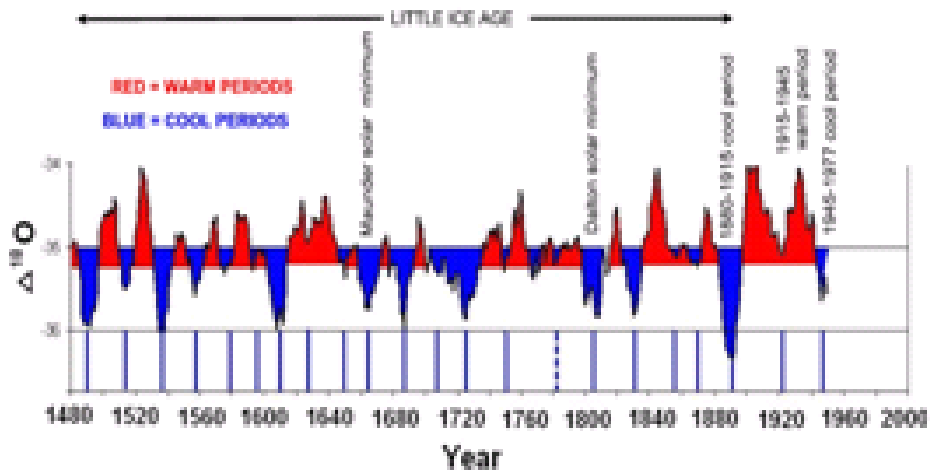


Figure 5.9.6.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460, based on data from Grootes and Stuiver, 1997). Also adapted from Easterbrook (2011).

Ice Age maximum advance was but the most recent in a series of advance/retreat cycles during the past several millennia, and its retreat “was the most dramatic episode of ice retreat in at least the last 1000 years.”

Some scientists argue, despite the fact human emissions did not reach significant levels until one-hundred years later, that the end of the Little Ice Age in the late nineteenth century was caused by CO₂-

induced global warming. Munroe *et al.* are not among this group. Instead, they contend both the birth and the death of the Little Ice Age were promoted by changes in solar irradiance, a conclusion supported by many other authors (Denton and Karlen, 1973; Bond *et al.*, 2001; Koch *et al.*, 2007). The quasi-periodic cycle of ~1,500 years that is involved also has been connected to glacier fluctuations in Europe (Holzhauser *et al.*, 2005; Matthews *et al.*, 2005;

Nussbaumer *et al.*, 2011). If these scientists are right about solar influences, then atmospheric CO₂ variability (which remained constant during several 1,500-year cycles during the Holocene) is likely to have played no significant role in recent temperature changes.

Conclusions

The history of North American montane glaciers demonstrates the occurrence of repeated cool/warm cycles, well before any possible influence by human-emitted CO₂. In terms of the currently observed climatic pattern driven by the PDO, glaciers are behaving precisely as they have in the past; i.e. are starting a new, cooler 25- to 30-year cycle. Extending this record into the future provides an opportunity to predict coming climate changes.

These findings stand in stark contrast to the IPCC-endorsed “hockey stick” temperature history of Mann *et al.* (1998, 1999), which neither matches the known history of glacial change nor portrays any Northern Hemispheric warming until around 1910.

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5.10 Sea and Lake Ice

Claims are commonly made that CO₂-induced global warming is melting sea ice in the Arctic, and potentially the Antarctic, and that such melting will accelerate as time passes.

Though semi-permanent sea ice exists today around the North Pole, fringing sea ice in both the Arctic and Antarctic is an annual, seasonal feature. Fringing sea ice is therefore particularly susceptible to fast advance or retreat depending upon local oceanographic and atmospheric changes. Quite major sea-ice changes are not uncommon and are not necessarily a result of climatic change; often, pulses of warm ocean water or atypical wind motions play a significant role.

Sea-ice expansion is driven by the spontaneous freezing of sea water in winter in areas of open polar ocean. Then, during the spring and summer months, and as daily solar radiation increases with higher Sun angle and longer day length, the sea ice melts and its area contracts. This annual cycle results in changes in area of sea ice of about 10 million km² each year in the Arctic and about 12 million km² in the Antarctic (see Figure 5.10.1).

The annual areal extent of sea ice is influenced by both ocean and atmospheric temperature, and in general the colder the winter the more sea ice that will form. The melting and break-up of sea ice is, however, more complex, in that winds and ocean currents often play a major role in breaking up, dispersing, and diminishing the area of sea ice, as was

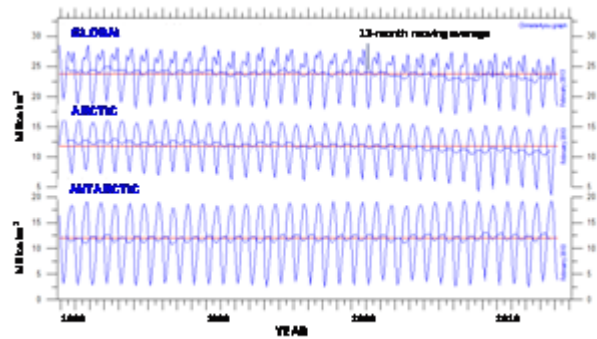


Figure 5.10.1. Arctic, Antarctic, and global sea ice area, 1979–2012 plotted using data from U.S. National Snow and Ice Data Center. Humlum, O. 2013. Sea ice extension in a longer time frame. Climate4You [Web site], <http://www.climate4you.com/SeaIce.htm>.

the case in the extensive diminution of ice in the Arctic Ocean in 2007 and 2012.

The freezing and melting of both land ice and sea ice is not just a simple function of temperature, but reflects complex changes in a number of environmental variables. The satellite observational record of sea ice spans only 1979–2012, and it has recently shown increases in ice area around Antarctica and decreases in area in the Arctic Ocean. There has been little net change in the overall global area of ice over the past 33 years, as shown in Figure 5.10.1. But 33 years is far too short a period of record from which to draw any meaningful conclusions about climate change.

Longer historical records demonstrate the area of Arctic ice has fluctuated in a multidecadal way in broad sympathy with past cycles in temperature, including shrinking to an area similar to that of recent years during periods of relative warmth in the 1780s and 1940s (see Figure 5.10.2) (Frauenfeld *et al.*, 2011). Earlier still, about 8,000 years ago during the early Holocene Climatic Optimum, geological records show temperatures up to 2.5^o C warmer than today resulted in strong Arctic glacier melt and therefore probably an almost or completely ice-free Arctic Ocean (e.g., Fisher *et al.*, 2006).

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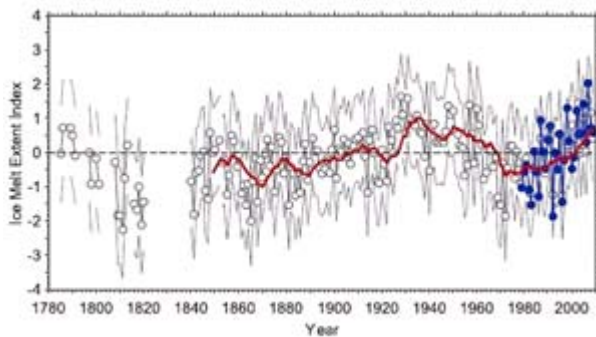


Figure 5.10.2. Estimated area of Arctic sea ice, 1780–2010. Adapted from Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784–2009. *Journal of Geophysical Research* **116**: doi:10.1029/2010JD014918.

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5.10.1 Arctic Sea Ice

Arctic climate is complex and varies on a number of timescales with multiple causes (Venegas and Mysak, 2000). Identifying changes in Arctic sea ice that can be attributed to an increase in temperature caused by the burning of fossil fuels has proved difficult. The task is further complicated because most of the records used in the debate comprise only a few years to a few decades of data, and they yield different trends depending on the data set or period of time studied.

The dynamic, rather than climatic, aspect of sea-ice change is well exemplified in a recent satellite study by Scott and Marshall (2010), who aimed to resolve a dilemma: Whereas there has been a trend toward earlier summer breakup of sea ice in western Hudson Bay, Canada, which some authors (Stirling *et al.*, 1999; Gagnon and Gough, 2005) have attributed to long-term warming in the region, Dyck *et al.* (2007) report no regional warming trend has elapsed sufficient to have caused this change.

Scott and Marshall combined passive microwave data collected by the Nimbus 7 satellite and Defense Meteorological Satellite Program satellites with Canadian Ice Service sea-ice charts (cf. Agnew and Howell, 2002; Fetterer *et al.*, 2008) to assemble a new sea-ice time series for the period 1971–2007. The new record shows “there has clearly not been a continuous

trend in the [time of sea-ice breakup] data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date.” The authors observe an increase in regional southwesterly winds during the first three weeks of June, with a corresponding increase in surface temperature, were the likely causes of the earlier breakup.

A necessary longer-term context for considering changes in sea ice has been provided by the reconstruction by Vare *et al.* (2009) of spring sea-ice trends in the central Canadian Arctic Archipelago over the past 1,200 years. These authors applied the biomarker IP25, using a technique developed by Belt *et al.* (2007). IP25 is a mono-unsaturated highly branched isoprenoid synthesized by sea-ice diatoms that live in sediments on the seabed below sea ice, the abundance of which varies according to the degree of ice cover. Using a core from Barrow Strait (74°16.05’N, 91°06.38’W), Vare *et al.* measured a variety of proxy data that included IP25, other organic biomarkers, stable isotope composition of bulk organic matter, benthic foraminifera, particle size distributions, and ratios of inorganic elements.

Vare *et al.* documented a decrease in spring sea ice between approximately 1,200 and 800 years before present, followed by an increase in ice over the last 400 years of their record (between 800 and 400 years BP). That the area of sea ice was less during the Medieval Warm Period and more during the Little Ice Age is a result that could have been expected. Nonetheless, together with the demonstration by Frauenfeld *et al.* of the presence also of multidecadal cycles in sea-ice area, this result confirms many other studies that suggest Arctic sea ice is widely variable and the variability is a manifestation of known natural climatic rhythmicities.

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Earlier research

Clearly, the science pertaining to causes of Arctic sea-ice loss is not settled, as confirmed by the following other recent studies that address the issue.

- Rothrock *et al.* (1999) used submarine sonar measurements to establish that Arctic sea ice in the mid-1990s had thinned by about 42 percent of the average 1958–1977 thickness. The IPCC reported this result, but then commented more recent studies have found the reduction in ice thickness occurred abruptly before 1991, rather than being gradual, and acknowledged “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) analyzed Arctic sea ice extent over the period 1978–1998 and found it to have decreased by about 14 percent. The change 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). This finding led them to suggest ice cover might be in a state of transition

which, if continued, “may lead to a markedly different ice regime in the Arctic,” as was also suggested by Vinnikov *et al.* (1999).

- Winsor (2001) analyzed a more comprehensive set of Arctic sea-ice data obtained from a transect of six submarine cruises conducted between 1991 and 1997. The transect data reveal mean Arctic sea-ice thickness had remained almost constant over the period of study. Data from the North Pole showed little variability, and a linear regression of the data revealed a “slight increasing trend for the whole period.” Combining these results with those from earlier studies, Winsor concludes “mean ice thickness has remained on a near-constant level around the North Pole from 1986 to 1997.”
- Parkinson (2000b) utilized satellite-derived data regarding sea-ice extent to calculate changes for the periods 1979–1990 and 1990–1999. 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 decadal trends are often reversed in this part of the world.
- Grumet *et al.* (2001) point out recent trends in Arctic sea-ice cover provide only “out of context” results, because their brevity does not allow for the consideration of interdecadal or multidecadal variability. Modern measurements of sea ice are simply available for too short a period for a climate trend to be demonstrated.

To overcome this problem, Grumet *et al.* developed a 1,000-year record of spring sea-ice conditions in Baffin Bay using sea-salt proxy records from an ice core from the Penny Ice Cap, Baffin Island. Their record demonstrates a period of reduced sea ice during the eleventh–fourteenth centuries, after which enhanced sea-ice conditions prevailed during the next 600 years. During the final (twentieth) century of the record period, “sea-ice conditions in the Baffin Bay/Labrador Sea region, at least during the last 50 years, are within ‘Little Ice Age’ variability.”

- Comiso *et al.* (2001) used 1979–1998 satellite imagery to analyze variability in the Odden ice tongue—a winter ice-cover blanket in the Greenland Sea with a length of about 1,300 km and an area up to 330,000 km². Surface air temperature data from nearby Jan Mayen Island provided the necessary meteorological record. Trend analyses revealed the ice tongue has exhibited no statistically significant change over the 20-year period considered. However, a proxy reconstruction of the Odden ice tongue for the

past 75 years suggested it was “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 Baltic Sea over the period 1720–1997. They report a significant decline in sea ice around 1877, with greater variability in sea-ice extent in the preceding, colder, 1720–1877 period than in the ensuing, warmer, 1878–1997 period.
- Jevrejeva (2001) reconstructed an even longer record of Baltic sea-ice variability by summarizing historical data for the annual date of ice breakup at the northern port of Riga, Latvia, for 1529–1990. The historical time series was best described by a fifth-order polynomial, which identified four distinct periods of climatic transition: 1530–1640, warming with a tendency toward earlier ice breakup of nine days/century; 1640–1770, cooling with a tendency toward later ice breakup of five days/century; 1770–1920, warming with a tendency toward earlier ice breakup of 15 days/century; and 1920–1990, *cooling* with a tendency toward later ice breakup of 12 days/century.
- Vinje (2001) studied a wide area of Nordic seas (the Greenland, Iceland, Norwegian, Barents, and Western Kara Seas) and determined “the extent of ice in the Nordic Seas measured in April has decreased by 33% over the past 135 years.” Nearly half of this reduction occurred over the period 1860–1900, which spans a period during which atmospheric CO₂ concentration rose by only 7 ppm, and a later time (of sea-ice decline, as it happens) when CO₂ concentration rose by more than 70 ppm. Vinje’s study clearly suggests the increase in the air’s CO₂ content over the past 135 years has had nothing to do with changes in sea-ice cover.
- In a similar study of the Kara, Laptev, East Siberian, and Chukchi Seas, based on newly available long-term Russian observations, Polyakov *et al.* (2002) found 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,” and these smaller-than-expected trends in sea-ice cover “do not support the hypothesized polar amplification of global warming.”
- Similarly, in a study published the following year, Polyakov *et al.* (2003) report “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.”

- Holloway and Sou (2002), employing data-fed model runs, found “no linear trend [in Arctic sea ice volume] over 50 years is appropriate” over the last half of the twentieth century, 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.” They conclude “the volume [of sea ice] estimated in 2000 is close to the volume estimated in 1950.”
- 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 data sets. For the newly extended period of 1972–2002, they determined Arctic sea ice extent had declined at a mean rate of $0.30 \pm 0.03 \times 10^6$ km² per decade, and for the shortened period from 1979–2002 they found a mean rate of decline of $0.36 \pm 0.05 \times 10^6$ km² per decade; i.e., a rate 20 percent greater than the full-period rate. Serreze *et al.* (2002) also determined the downward trend in Arctic sea ice extent during the passive microwave era culminated with a record minimum value in 2002.
- 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. The latitudes, between 65° and 81.5°N, covered the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. The measurements revealed “an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models,” undermining “the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent.” The researchers also showed “sea ice mass can change by up to 16% within one year,” all of which “contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming.”

Laxon *et al.* show errors are present in current simulations of Arctic sea ice and conclude, “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 for 1979–1997 using monthly fields of ice motion obtained from the International Arctic Buoy Program. Their analysis indicated sea ice formed over shallow Arctic seas is transported across the central basin to be exported primarily through Fram Strait and, to lesser degrees, the Barents Sea and Canadian Archipelago. Within the central Arctic, the ice travel times for this journey averaged 4.0 years from 1984–85 through 1988–89, but only 3.0 years from 1990–91 through 1996–97. The enhanced rate of modern ice export to Fram Strait from the Beaufort Gyre reduced the amount of thick-ridged ice within the Arctic central basin of the Arctic and helped produce the sea-ice thinning observed in the 1980s and 1990s. Pfirman *et al.* comment the rapid change in ice dynamics between 1988 and 1990 was a “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].”

- Kwok (2004) used QuikSCAT backscatter, MY fractions from RADARSAT, and the record of ice export from satellite passive microwave observations to study Arctic sea-ice changes for 1999–2003. Their results show the coverage of Arctic MY sea ice at the beginning of each year of the study was 3,774 x 10³ km² in 2000, 3,896 x 10³ km² in 2001, 4,475 x 10³ km² in 2002, and 4,122 x 10³ km² in 2003, which represents an increase in sea-ice coverage of 9 percent overall.

- Belchansky *et al.* (2004) report the total Arctic January multiyear ice area declined at a mean rate of 1.4 percent per year for the period 1988–2001. In the autumn of 1996, however, they note, “a large multiyear ice recruitment of over 10⁶ km² fully replenished the previous 8-year decline in total area.” This replenishment was followed by an accelerated and compensatory decline during the subsequent four years. Though the period of study is too short to be conclusive, Kwok (2004) reports 75 percent of the interannual variation in January sea-ice area was explained by linear regression on two atmospheric parameters: the previous winter’s Arctic Oscillation index (a proxy for melt duration) and the previous year’s average sea level pressure gradient across the Fram Strait (a proxy for annual ice export).

- Heide-Jorgensen and Laidre (2004) examined

changes during 1979–2001 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. 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% per decade. In contrast, in Baffin Bay-Davis Strait and northern Baffin Bay the open-water trend was downward, and at a mean rate for all open-water microhabitats studied of fully 1% per decade, and in Lancaster Sound the open-water trend was also downward, this time at a mean rate of 0.6% per decade.

In comparison with these open water changes, Heide-Jorgensen and Laidre report “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 were detected back to 1953 along the West Greenland coast by Stern and Heide-Jorgensen (2003).

- Bamber *et al.* (2004) used high-accuracy ice-surface elevation measurements (from Krabill *et al.*, 2000) to evaluate 1996–2002 elevation changes in the largest icecap in the Eurasian Arctic—Austfonna, on the island of Nordaustlandet in northeastern Svalbard. The authors discovered the central and highest-altitude area of the icecap, 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.” The highest of these growth rates represents as much as a 40 percent increase in accumulation rate (Pinglot *et al.*, 2001).

Bamber *et al.* conclude the best explanation for the dramatic increase in icecap growth over the six-year study period is a large increase in precipitation associated with a concomitant reduction in sea-ice cover in this sector of the Arctic. They characterize the situational change by saying it simply represents the transfer of ice from the top of the sea (in this case, the Barents Sea) to the top of the adjacent land (the Austfonna icecap).

- Divine and Dick (2006) used historical April–August ice observations from Iceland, Greenland, Norwegian, and Barents Seas between 30°W to 70°E to construct time series of ice-edge positions for 1750–2002. The results showed the presence of

oscillations in ice cover with periods of about 60 to 80 years and 20 to 30 years, superimposed on a continuous negative trend corresponding to the “persistent ice retreat since the second half of the 19th century.” This retreat began well before anthropogenic CO₂ emissions could have had a measurable effect on Earth’s climate.

- Gagnon and Gough (2006) analyzed sea-ice variability in Hudson Bay, Canada (cf. Parkinson *et al.*, 1999) using data from 13 stations located along the shoreline of Hudson Bay (seven) and in surrounding nearby lakes (six). They compiled long-term weekly measurements of ice thickness and associated weather conditions for the period 1963–1993, discovering a statistically significant thickening of the ice cover over time occurred in western Hudson Bay, while a small, non-significant thinning occurred on the eastern side. These findings contradict the projections from general circulation models and also “the reduction in sea-ice extent and thickness observed in other regions of the Arctic.”

- Over the longer time scale, a study by Eldrett *et al.* (2007) provides further evidence that the IPCC’s view of melting sea ice is wrong. They used dinocyst fossils and palaeomagnetic dating to generate a new stratigraphy for three key northern Deep Sea Drilling Project/Ocean Drilling Program sites, finding evidence of “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.” The data “indicate sediment rafting by glacial ice, rather than sea ice, and point to East Greenland as the likely source,” thus suggesting “the existence of [at least] isolated glaciers on Greenland about 20 million years earlier than previously documented.”

What is particularly interesting about these findings, as Eldrett *et al.* describe them, is they indicate the presence of glacial ice on Greenland at a time when ocean bottom-water temperatures were 5–8°C warmer and atmospheric CO₂ concentrations as much as four times greater than they are today.

Conclusions

The papers discussed above provide a litany of detailed findings as to the variability of Arctic sea-ice cover in association with natural changes in atmospheric, oceanographic, or ice dynamics. So far as specific changes are concerned—for example the widely reported thinning of Arctic sea ice during the 1990s—no evidence exists that such changes were forced by an increase in atmospheric CO₂ content.

Instead, the oscillatory behavior reported in so many ice studies implies the existence of “close connections between the sea ice cover and major oscillatory patterns in the atmosphere and oceans” (Parkinson, 2000b). This includes, *inter alia*, connections with 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); the spatially broader Arctic Oscillation (e.g., Deser *et al.*, 2000; Wang and Ikeda, 2000); the Arctic Ocean Oscillation (Polyakov *et al.*, 1999; Proshutinsky *et al.*, 1999); the “see-saw” in winter temperatures observed between Greenland and northern Europe (Rogers and van Loon, 1979); and an interdecadal Arctic climate cycle (Mysak *et al.*, 1990; Mysak and Power, 1992).

As concluded by Parkinson (2002), “The likelihood that Arctic sea ice trends are the product of such natural oscillations 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.”

No substantial research study, including the papers discussed above, has demonstrated the level of sea ice in the Arctic Ocean stood at some “ideal” level prior to the Industrial Revolution. Instead, it is manifestly obvious that Arctic sea-ice cover varies dramatically and naturally over quite short periods of geological time. It is also clear Arctic fauna and flora, including the iconic polar bear, are well adapted to deal with the environmental exigencies that result. Regarding environmental policy formulation, it has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or human economic perspective.

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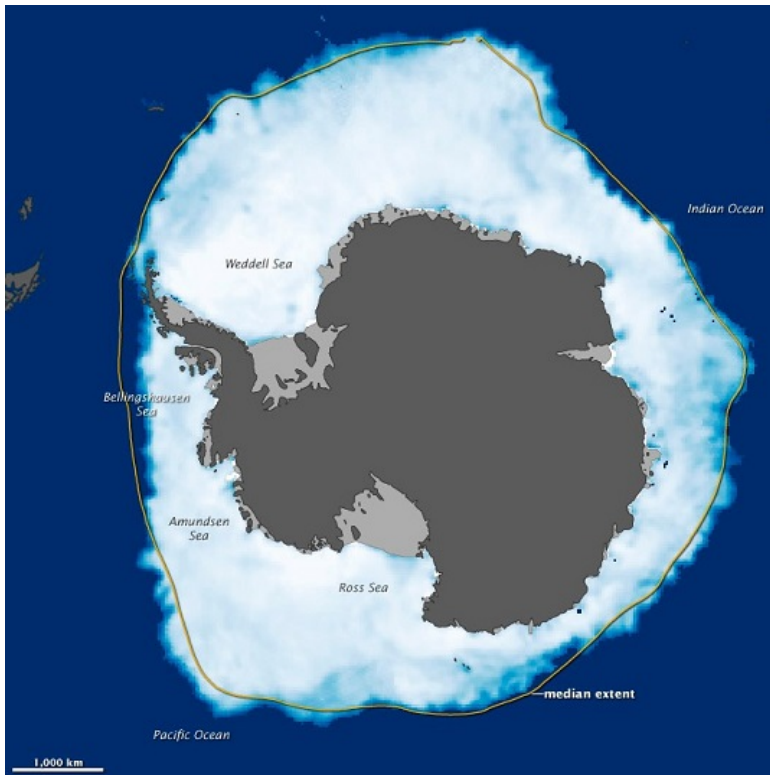
5.10.2 Antarctic Sea Ice

Antarctic sea ice behavior continues to defy the expectations of those who believe that it should be shrinking rapidly under the influence of human-induced global warming (Figure 5.10.2.1). This is not a new finding, and other studies that have addressed this issue are listed below.

Landfast sea ice (fast ice) is sea ice held stationary by being attached to coastal features such as a rocky shoreline, glacier tongue, ice shelf, or grounded iceberg or shoal. Such fast ice is “a preeminent feature of the Antarctic coastal zone and an important interface between the ice sheet and pack ice/ocean” (Fraser *et al.*, 2012). Variability in fast ice extent is often viewed as a sensitive indicator of climate change (Murphy *et al.*, 1995; Heil *et al.*, 2006; Mahoney *et al.*, 2007).

Fraser *et al.* (2012) developed a high-resolution time series of landfast sea ice extent along the East Antarctic coast for the period March 2000–December 2008 using data from the MODIS (Resolution Imaging Spectroradiometer) satellite. The ice area study across East Antarctica (10°W to 172°E) revealed a statistically significant increase of $1.43 \pm 0.3\%$ per year, this trend agreeing with other short-term regional trends in overall sea ice (pack ice + fast ice) for different sectors of the coast (Cavalieri and Parkinson, 2008; Comiso, 2009).

Pezza *et al.* (2012) also report a modest increasing trend in sea-ice area around Antarctica over the era of satellite coverage, as documented by Watkins and Simmonds (2000), Zwally *et al.* (2002), Parkinson (2004), Turner *et al.* (2007), and Comiso and Nishio (2008). Pezza *et al.*'s broader study derived a history of Antarctic sea ice for 1979–2008, based upon remotely sensed data from the NASA's Nimbus-7 SMMR and DMSP SSM/I passive microwave satellites. The results showed modest trends of increasing sea ice during all seasons, with the trends over spring and autumn being the most pronounced, involving an increase of about half-a-million square kilometers over the whole period. This equates with a 2–3 percent increase in sea-ice area during winter and spring and a 5–7 percent increase during summer. Pezza *et al.* report “the greatest [sea ice area] on record occurred during the 2007–2008 summer” when an increase in area of 8 percent occurred.



Southern Hemisphere sea ice anomaly from 1979-2008 mean

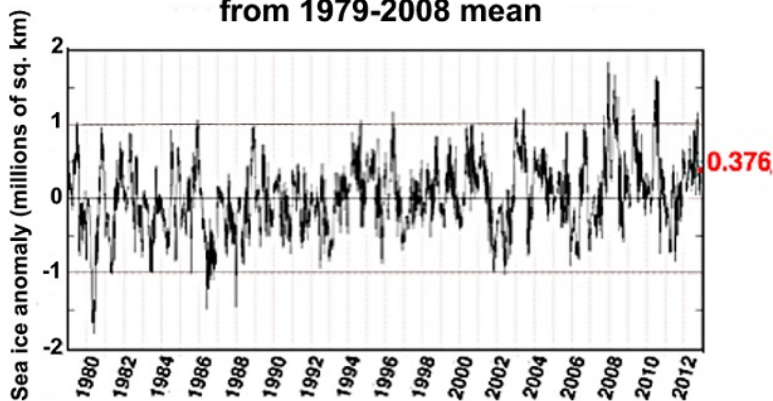


Figure 5.10.2.1. ABOVE Record sea ice area around Antarctica, attained in 2012 (NASA, 2012). BELOW Increase in Antarctic sea ice area since 1979 (graph from *Cryosphere Today*, University of Illinois).

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Earlier Research

Antarctic sea ice behavior continues to defy the expectations of those who believe it should be shrinking rapidly under the influence of human-induced global warming. This is not a new finding;

other studies that have addressed this issue are summarized below.

- Watkins and Simmonds (2000) analyzed trends in sea ice that surrounds Antarctica using data for 1987–1996 collected by the Special Sensor Microwave Imager (SSM/I) on United States meteorological satellites. Statistically significant increases in the area and extent of sea ice³ were recorded over the period studied, and when the new data were combined with results for the preceding period of 1978–1987, sea ice continued to show increases over the summed period (1978–1996).
- Watkins and Simmonds' findings that Southern Ocean sea ice has increased in area, extent, and season length since at least 1978 are supported by other studies. Hanna (2001) provided an analysis of sea ice cover based on SSM/I data for 1987–1999 and found “an ongoing slight but significant hemispheric increase of $3.7 \pm 0.3\%$ in extent and $6.6 \pm 1.5\%$ in area.” Parkinson (2002) utilized satellite passive-microwave data to map the length of the sea-ice season throughout the Southern Ocean for each year of the period 1979–1999, finding 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 1978–2002, Parkinson (2004) reported a linear increase in 12-month running means of Southern Ocean sea ice extent of $12,380 \pm 1,730 \text{ km}^2$ per year.
- Elderfield and Rickaby (2000) conclude the sea-ice cover of the Southern Ocean during glacial periods may have been as much as double the coverage of modern winter ice. They suggest by restricting communication between the ocean and atmosphere, sea-ice expansion provides a mechanism for reduced CO₂ release by the Southern Ocean and thereby lower glacial atmospheric CO₂ during glaciations.
- 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, finding, among other things, the mean trend in the latitudinal location of the Antarctic sea-ice edge over the prior 18 years was an equatorward expansion of ice by 0.011° of latitude per year.

³ The *area* of sea ice is defined as the summed area of ice not including enclosed gaps and leads; the *extent* of sea ice is always a greater number and is measured inclusive of gaps and leads.

- 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 the sea ice extent of the entire Southern Ocean increased by $11,181 \pm 4,190$ square km per year, or by $0.98 \pm 0.37\%$ per decade, while sea-ice area increased by nearly the same amount: $10,860 \pm 3,720$ square km per year, or by $1.26 \pm 0.43\%$ per decade. They observed the variability of monthly sea-ice extent declined from 4.0% over the first 10 years of the record to 2.7% over the last 10 years.
- Vyas *et al.* (2003) analyzed data from the multichannel 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 derived from passive microwave radiometers aboard earlier Nimbus-5, Nimbus-7, and DMSP satellites to study secular trends in sea-ice extent about Antarctica over the period 1978–2001. This work revealed a mean rate of increase in sea-ice extent for the entire Antarctic region of 0.043 million km² per year. Vyas *et al.* note also “the increasing trend in the sea ice extent over the Antarctic region may be slowly accelerating in time, particularly over the last decade,” commenting 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 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 data sets with National Ice Center digital sea ice data. They found between 1977 and 2002 sea-ice extent around Antarctica increased at a mean rate of $0.10 \pm 0.05 \times 10^6 \text{ km}^2$ per decade.
- Similarly, Liu *et al.* (2004) used sea-ice concentration data 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 for 1979–2002. They found “overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (of $\sim 4,801 \text{ km}^2/\text{yr}$.” In addition, they determined the total Antarctic sea ice increased by $\sim 13,295 \text{ km}^2/\text{yr}$, at a greater than 95% confidence

level.

- 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 for five longitudinal sectors emanating from the South Pole. Laine concludes “sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero.” Laine also reports “the Antarctic region as a whole and all the sectors separately show slightly positive spring-summer albedo trends.”
- Comiso and Nishio (2008) provide updated and improved estimates of trends in Arctic and Antarctic sea ice cover for the period 1978–2006 using data from the Advanced Microwave Scanning Radiometer (AMSR-E), the SSM/I, and the SSMR, where the data from the last two instruments were adjusted to be consistent with the AMSR-E data. Their findings indicate sea-ice extent and area in the Antarctic grew by $+0.9 \pm 0.2$ and $+1.7 \pm 0.35\%$ per decade, respectively.
- Cavalieri and Parkinson (2008) extend the analyses of sea ice time series reported by Zwally *et al.* (2002) from 20 years (1979–1998) to 28 years (1979–2006), based upon satellite-borne passive microwave radiometer data. The results indicate “the total Antarctic sea ice extent trend increased slightly, from $0.96 \pm 0.61\%$ per decade to $1.0 \pm 0.4\%$ per decade, from the 20- to 28-year period.” Corresponding numbers for Antarctic sea ice area trends were $1.2 \pm 0.7\%$ per decade and $1.2 \pm 0.5\%$ per decade. 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.

Conclusions

Since they first became available in 1979, satellite-mounted sensors have provided evidence for the multidecadal growth of both pack ice and fast ice across the entire East Antarctic region, and this expansion continues today. These observations contradict the climate modeling that projects decreases in Antarctic sea ice.

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5.10.3 Lake Ice

Floating ice pack responsive to climatic fluctuations forms on large, intracontinental lakes as well as on the ocean, and Wang *et al.* (2010) provide an analysis of 70 years of such floating ice for the Great Lakes of North America. Their study covers the winters of 1972–73 to 2008–09 and comprises an analysis of time series of annual average ice area and basin winter average surface air temperature (SAT) and floating ice cover (FIC) for the Great Lakes, which they remind us “contain about 95% of the fresh surface water supply for the United States and 20% of the world.”

The primary data of interest are depicted in Figure 5.10.3.1, which shows after an initial four years of relative warmth and lower annual average ice area, SATs declined and FIC area rose. Then there began a long period of somewhat jagged SAT rise and FIC decline, both of which level out from about 1998 to 2006, after which SAT once again slowly declines and FIC slowly rises. Both parameters terminate at about the same value they exhibited initially.

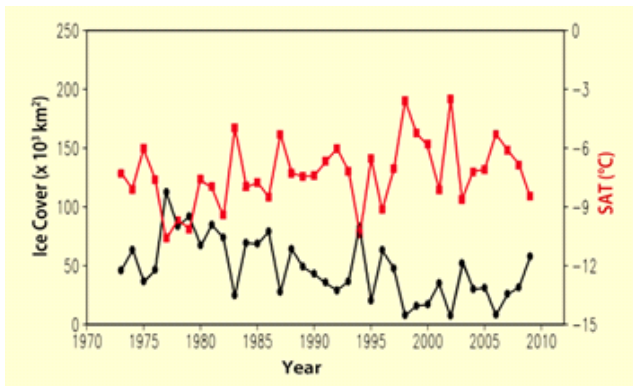


Figure 5.10.3.1. Annual average ice area of the North American Great Lakes and basin winter average surface air temperature (SAT) vs. time. Adapted from Wang, J., Bai, X., and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. *EOS, Transactions, American Geophysical Union* **91**: 41–42.

Conclusions

Wang *et al.* (2010) conclude “natural variability dominates Great Lakes ice cover” and the short-term trends present are “only useful for the period(s) studied.” There is therefore no reason to attribute any change in the annual average ice area of the North American Great Lakes to anthropogenic global warming. Similarly, Yoo and D’Odorico (2002) have shown northern high-latitude ice break-up follows a natural multidecadal rhythm rather than conforming to any long-term linear melting trend.

References

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5.11 Late Pleistocene Glacial History

Geological studies have established that during the most recent major deglaciation since 20,000 years ago, multiple intense and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. This geological record of past climatic events provides an essential context missing from many current discussions of modern ice volume changes and their significance.

The results of oxygen isotope measurements from ice cores in the Greenland and Antarctic ice sheets several decades ago (see Section 5.7) stunned the scientific world (Dansgaard, 1987; Dansgaard and Oeschger, 1989; Dansgaard *et al.*, 1969, 1970, 1971, 1982, 1984, 1989; Jouzel *et al.*, 1987a, b, 1989; Oeschger *et al.*, 1983). Among the surprises was the delineation of multiple abrupt and intense periods of warming and cooling with a 1,500-year periodicity, which have come to be called Dansgaard-Oeschger (or D-O) events. The most precise records of these changes are the ice cores from the Greenland Ice Sheet Project (GISP) and the Greenland Ice Core Project (GRIP), which are especially important because the age of the ice at various levels in the cores has been established by counting annual layers, yielding a very accurate chronology of climatic fluctuations.

The Greenland GISP2 ice core shows temperatures for the past 100,000 years, of which the last 50,000 are presented in Figure 5.11.1 (upper). The later part of the last ice age (50,000–20,000 y BP) was followed by spasmodic and abrupt warming at the start of the Holocene at 11,700 y BP. More than a dozen episodes of abrupt warming and cooling occurred within the past 50,000 years, all of which accords well with other geologic evidence that had previously led to the recognition of several periods of warming and cooling. The named climatic periods, of which the cold Younger Dryas interval is the best

Observations: The Cryosphere

known (Figure 5.11.1, lower), were established from geological land studies long before their equivalents were recognized in deep sea mud cores and polar ice cores. In decreasing age, the major post-glacial climatic episodes delineated by geological studies comprise the Oldest Dryas (cold) Period, the Bølling (warm) Period, the Older Dryas (cold) Period, the Allerød (warm) Period, the Inter-Allerød (cold) Period, and the Younger Dryas (cold) Period.

The *Oldest Dryas Period* lasted between about 18,000 and 15,000 years BP (Roberts, 1998), with ^{14}C dates from the northwest shore of Lake Neuchâtel in Switzerland placing its termination at 14,650 y BP. Data derived from isotope variation of nitrogen and argon trapped in Greenland ice samples gives a second high-resolution date for the sharp temperature rise that ended it, 14,670 y BP. The significance of the Oldest Dryas is the abruptness of the warming that terminated it, during which temperatures in Greenland rose about 13°C in only a few centuries (Grootes and Stuiver, 1997; Cuffey and Clow, 1997).

The Greenland oxygen isotope record shows the *Bølling Warm Period* to lie between 14,600 and 14,100 BP. Abrupt, intense warming 14,500 years ago resulted in sudden wholesale melting of the huge continental ice sheets that covered North America, Europe, and Russia, and also an extensive retreat of alpine glaciers in discrete mountainous areas. This warming was remarkable because of both its abrupt onset and its intensity. Temperatures in Greenland rose $\sim 12^{\circ}\text{C}$ (which equals almost the total cooling of the late Pleistocene glaciation) to near present-day levels in about one century. As a result of the sudden, intense warming and melting, sea level rose sharply by perhaps as much as 18 m (Deschamps *et al.*, 2012). Although these temperature changes are cited for Greenland, simultaneous glacial retreats all over the world indicate the Bølling warming was global and characterized by temperatures at near-modern levels.

The Bølling was terminated by temperatures plummeting again from the thermal maximum by about 11°C in a few hundred years, thus initiating the *Older Dryas Period* from 14,300 to 14,000 BP. Temperatures returned to near full glacial level, and glaciers halted their rapid retreat.

About 14,000 years BP, temperatures rose abruptly again, and the *Allerød Warm Period* began and lasted until 12,800 years BP. Though the Allerød

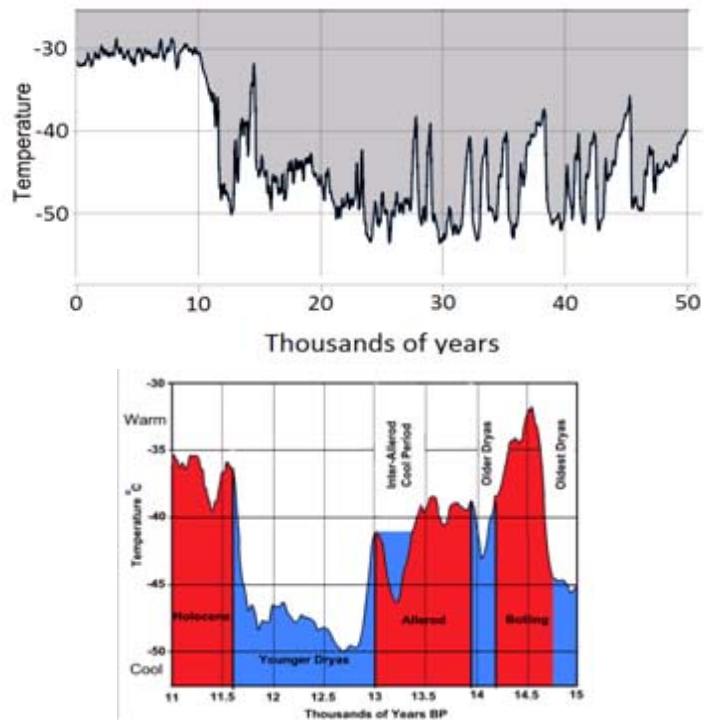


Figure 5.11.1. ABOVE. Greenland GISP2 air temperature curve for the past 50,000 years. Adapted from Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396. BELOW. Late glacial temperature fluctuations in the GISP2 Greenland ice core. Red = warm periods, blue = cold periods. Data from Cuffey and Clow (1997) and Alley, R.B. 2000, The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

was not as warm as today, or as during the Bølling, the rate of warming was still rapid, at $\sim 4.5^{\circ}\text{C}/\text{century}$. The interstadial ended abruptly with a cold period that reduced temperatures back to near-glacial levels within a decade.

Near the end of the Allerød warm period, temperatures dropped precipitously by $\sim 8^{\circ}\text{C}$ in about a century, to delineate what is called the *Inter-Allerød (cold) Period* (Grootes and Stuiver, 1997; Cuffey and Clow, 1997). Temperatures returned to nearly full Ice Age levels but persisted for only a few hundred years, so glaciers halted their retreat but did not rebuild to former extents. Then, just as suddenly as it had cooled, abrupt warming of $\sim 5^{\circ}\text{C}$ occurred, and temperatures returned to Allerød levels. In the Southern Hemisphere, the Allerød warming was interrupted by a colder period known as the *Antarctic Cold Reversal*, which lasted from $\sim 13,500$ - 13,000 year BP (Grootes and Stuiver, 1997; Cuffey and Clow, 1997). This reversal is well documented in Antarctic

ice cores and also by glacial advances that occurred in New Zealand and are represented by the Birch Hill and Macaulay moraines in the Tekapo Valley of the Southern Alps (Easterbrook *et al.*, 2011).

The *Younger Dryas* is the longest and coldest of several very abrupt climatic changes near the end of the Pleistocene. It comprised a period of cold lasting about 1,300 years and ended as abruptly as it started. At the start of the event, 12,800 years ago, temperatures plunged $\sim 8^{\circ}\text{C}$ to full glacial levels. Glaciers, including remnants of the continental ice sheets, re-advanced, leaving moraines as footprints of their former presence. The end of the Younger Dryas occurred when temperatures rose sharply by $\sim 12^{\circ}\text{C}$ over about 50 years, to terminate the Pleistocene ice age about 11,500 years ago.

Radiocarbon and isotope dating of glacial moraines in regions all over the world, and abrupt steps in oxygen isotope ratios in the Greenland and Antarctic ice cores, indicate the Younger Dryas cooling was both globally widespread and synchronous. Evidence of Younger Dryas ice advance is reported from the Scandinavian ice sheet, the North American Laurentide and Cordilleran ice sheets, and the Russian ice sheet. Alpine and icecap glaciers also advanced during Younger Dryas cooling in both the Northern and Southern hemispheres, including many places in the Rocky Mountains of the United States and Canada, the Cascade Mountains of Washington in the United States, the European Alps, the Southern Alps of New Zealand, and the Patagonian Andes Mountains of South America.

The Younger Dryas cooling was not just a single climatic event. Not only did climatic warming and cooling occur both before and after it, but significant climate fluctuations also occurred within the Younger Dryas. That these were global events in both hemispheres is shown not only by correlations between ice cores from Greenland and Antarctica but also by the presence of dated, multiple glacial moraines around the world (Easterbrook *et al.*, 2011).

Figure 5.11.2 shows a plot of oxygen isotope variation within the Younger Dryas. Temperatures fluctuated up and down at least a dozen times, some brief warming periods reaching near-Allerød levels. Radiocarbon and cosmogenic dating of glacial moraines, and abrupt changes in oxygen isotope ratios in ice cores, indicate the Younger Dryas cooling was globally synchronous. That these climatic fluctuations were global in extent is shown by the occurrence of multiple Younger Dryas moraines around the world.

The type locality for the Younger Dryas is in Scandinavia, where the Scandinavian Ice Sheet

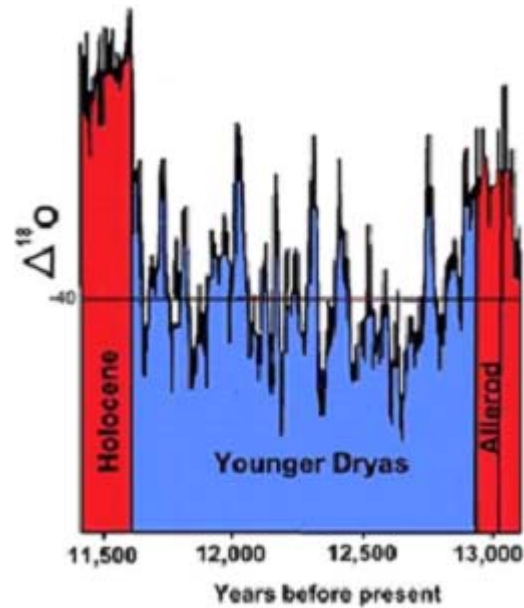


Figure 5.11.2. Oxygen isotope record from the Greenland ice core showing an abrupt temperature drop 12,800 years ago, 1,300 years of cool climate, and sudden warming 11,500 years ago (plotted from data in Grootes and Stuiver, 1997).

deposited two extensive Salpausselka end moraines across southern Finland, the central Swedish moraines, and the Ra moraines of southwestern Norway during the Younger Dryas. ^{14}C dates suggest an age of $\sim 10,700$ y BP for the outer Salpausselka moraine and $\sim 10,200$ y BP for the inner moraine, very similar to Younger Dryas moraines of the Cordilleran and Ice Sheets in North America. Thus, all three major Pleistocene ice sheets experienced multiple moraine-building episodes during the Younger Dryas.

Multiple Younger Dryas moraines also occur at Loch Lomond in the Scottish Highlands (e.g., Sissons, 1980; Ballantyne, 2002, 2006; Benn and Ballantyne, 2005; Bennett and Boulton, 1993; Rose *et al.*, 1998). Alpine glaciers and icefields in Britain readvanced or re-formed during the Younger Dryas and built extensive moraines at glacial margins. The largest Younger Dryas icefield at this time was the Scottish Highland glacier complex, but smaller alpine glaciers occurred in the Hebrides and Cairngorms of Scotland (Sissons, 1980), in the English Lake District, and in Ireland. The Loch Lomond moraines consist of one to several moraines, sometimes multiple, nested, recessional moraines. Radiocarbon dates constrain the age of the Loch Lomond moraines between 12.9 and 11.5 cal y BP.

Further south, in the Swiss Alps near St. Moritz, a complex moraine system contains two main moraine

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ridges. The outer moraine has been dated by ^{10}Be , ^{26}Al , and ^{36}Cl at 11.75 ka and the inner moraine at 10.47 ka (Ivy-Ochs *et al.*, 1996, 1999; Kerschner *et al.*, 1999). At Maloja Pass, less than 10 km from Julier Pass, a bog just inside the outermost of three Egesen moraines was ^{14}C dated at 10,700 y B.P. (Heitz *et al.*, 1982).

post-LGM fluctuations of the CIS (Easterbrook, 1963, 1992, 2010; Easterbrook *et al.*, 2007; Kovanen and Easterbrook, 2002). The chronology of the ice margin fluctuations and timing of ice retreat during the Sumas Stade (Figure 5.11.3) are bracketed by 70 radiocarbon dates and tied to morphologic and stratigraphic evidence. The CIS chronology, which

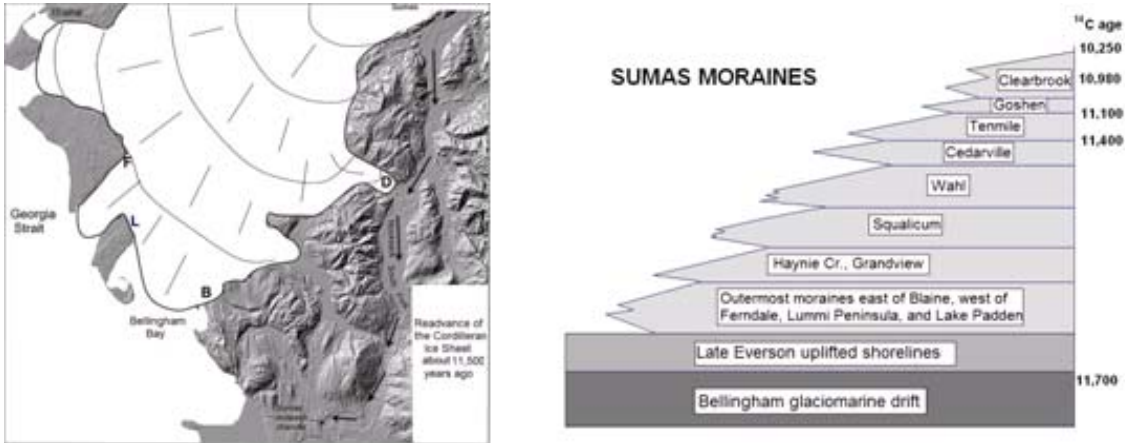


Figure 5.11.3. LEFT Reconstruction of the Cordilleran ice sheet at the end of the Pleistocene, 11,500 ^{14}C yrs. ago, NW Washington USA. RIGHT, Depiction of multiple Younger Dryas moraines from the Cordilleran ice sheet. From Easterbrook, D.J. 2012. Part 2 of Professor Don Easterbrook's concerns about the "Shakun *et al.* paper." Climate Observer [Web site] <http://climateobserver.blogspot.com/2012/04/part-2-of-professor-don-easterbrooks.html>.

Despite early evidence that a similar late-glacial readvance occurred in western North America (Armstrong, 1960; Easterbrook, 1963; Armstrong *et al.*, 1965), the apparent absence of the marker pollen evidence led some to believe the Younger Dryas did not occur in North America. Recent research has established the effects of the Younger Dryas as widespread at localities in the Pacific Northwest (Easterbrook, 1994a,b, 2002, 2003a,b; Easterbrook and Kovanen, 1998; Kovanen and Easterbrook, 2001, 2002), the Rocky Mountains (Licciardi *et al.*, 2004, Gosse *et al.*, 1995a,b; Easterbrook *et al.*, 2004), and California (Owen *et al.*, 2003). Planktonic microfossil records from the Pacific Northwest and Alaska also confirm the presence of a Younger Dryas event, with alkenone estimates of sea surface temperatures west of Vancouver Island indicating a temperature drop of 3°C (Kienast and McKay, 2001).

Morphologic, stratigraphic, and chronologic evidence of multiple moraines associated with oscillations of the remnants of the Cordilleran Ice Sheet (CIS) in the Fraser Lowland of British Columbia and Washington has revealed multiple

closely matches that of the GISP2 and GRIP ice cores from Greenland and sea surface temperatures in the north Pacific (Kienast and McKay, 2001), also compares well with the chronology of post-LGM alpine moraines in the western United States

Elsewhere in North America, Younger Dryas deposits are associated with an advance of the Laurentide Ice Sheet with dated moraine deposition in SW Canada (Grant and King, 1984; Stea and Mott, 1986, 1989); the expansion of cirque glaciers in the Wind River Range, Wyoming (Gosse *et al.*, 1995) and Sawtooth Range, Idaho (Easterbrook *et al.*, 2011); extensive moraine and ice-contact sediment deposition in the North Cascade Mountains (Kovanen and Easterbrook, 2001; Easterbrook *et al.*, 2010); cirque moraines in the Mt. Rainier part of the Cascade Range (Crandell and Miller, 1974); and multiple moraines near Icicle Creek (Page, 1939; Porter, 1976; Long, 1989; Easterbrook *et al.*, 2011).

In the Southern Hemisphere, multiple Younger Dryas moraines occur in the Southern Alps of New Zealand, for example at Arthur's Pass and at Birch Hills along Lake Pukaki. At the latter locality the

Younger Dryas moraines are located ~40 km up-valley from the last glacial maximum moraines. Younger Dryas moraines also occur at Prospect Hills in the Arrowsmith Range (Burrows, 1975) (Figure 5.11.4), and on the west coast of South Island, where wood in the Waihao Loop moraine, deposited by the Franz Josef Glacier about 20 km behind the LGM moraine, has been dated at 11,200 ^{14}C y BP (Mercer, 1982, 1988; Denton and Hendy, 1994).

Conclusions

Since the last glaciation, repeated rapid and often synchronous warmings and coolings have occurred across the globe, accompanied by concomitant glacial retreat and advance. The magnitude and intensity of these climatic fluctuations have been up to 20 times greater than modern warming during the past century.

The Younger Dryas is perhaps the most important of the climatic episodes, and the multiple nature of its moraines in both hemispheres indicates the occurrence of multiple climatic pulses (see Figure 5.11.5). The absence of a time lag between the Northern and Southern Hemisphere glacial fluctuations precludes an oceanic cause such as the North Atlantic Deep Ocean Water hypothesis for the cause of the Younger Dryas. Nor does a singular cosmic impact or volcanic origin seem likely because multiple Dansgaard/Oerscher warming and cooling events have recurred over periods of tens of thousands of years.

The most likely causation of the millennial rhythmicity that modulates major glacial-interglacial episodes is fluctuations in solar activity. What is certain is that none of the events were forced by changes in atmospheric carbon dioxide.

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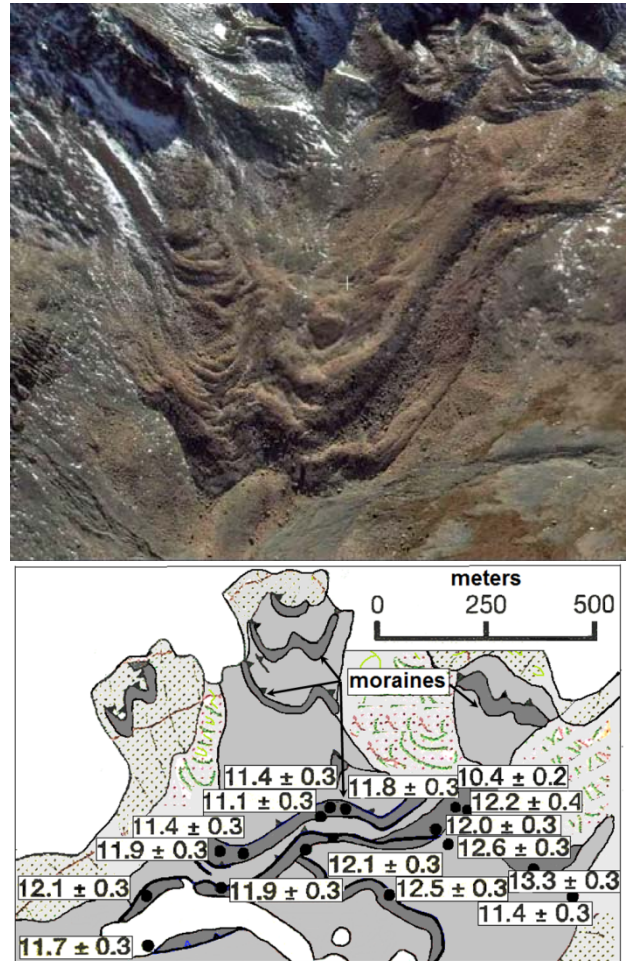


Figure 5.11.4. Moraines of the Younger Dryas ice advance in Irishman Basin, New Zealand Southern Alps. TOP: Aerial photograph. BOTTOM: Cosmogenic dates in thousands of years. Adapted from Kaplan, M.R., Schaefer, J.M., Denton, G.H., Barrell, D.A., Chinn, T.J.H., Putnam, A.E., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A.M. 2010. Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* **3**: 194–197.

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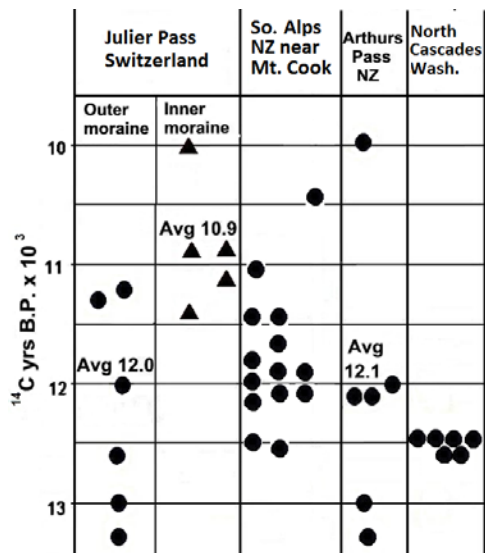


Figure 5.11.5. Ages of Younger Dryas moraines in New Zealand and the Swiss Alps. Adapted from Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149; and Easterbrook, D.J., Gosse, J., Sherrard, C., Stevemsp, E.B., and Finkel, R. 2011. Evidence for synchronous global climatic events: cosmogenic exposure ages of glaciations. In: *Evidence-Based Climate Science*, Easterbrook, D.J. (Ed.), pp. 53–88.

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5.12 Holocene Glacial History

The climatic changes seen during the late Pleistocene continued, albeit at a lesser amplitude than for Dansgaard-Oeschger events, during the last 11,700 years (Holocene Period). Holocene climatic variability is well encapsulated by the temperature curve inferred from oxygen isotope measurements in Greenland ice cores (see Figure 5.12.1).

The five most important characteristics of the documented variability are the presence of a temperature peak about 2° C warmer than today during the Holocene climatic optimum, ~8,000 y BP; the general cooling trend that occurred thereafter; the punctuation of the record by 1,500-year-long alternating rhythms of warmer and colder climate (the Bond Cycle, of probable solar origin: Bond *et al.*, 1997; Wanner *et al.*, 2008); that for the great majority of the last 10,000 years temperature has been warmer than today; and that none of the climatic fluctuation during the Holocene was accompanied by parallel fluctuations in carbon dioxide.

A conspicuous larger climatic event occurred 8,200 years ago, when the Holocene record was interrupted by a sudden global cooling that lasted for 200 years (Figure 5.12.2). During this time, alpine glaciers advanced and built moraines (Easterbrook, 2011). Neither the abrupt climatic cooling nor the abrupt warming that followed was accompanied by atmospheric CO₂ changes.

Most of the climatic episodes indicated by the Greenland climate record also were recorded by historic sources. Egyptian records from before the founding of the Roman Empire show a cool climatic period from about 750 to 450 BC, with the Tiber River freezing and snow remaining on the ground for long periods (Singer and Avery, 2007). The Roman Warm Period (200–600 AD) followed, when the Romans wrote of grapes and olives growing farther north in Italy than had been previously possible.

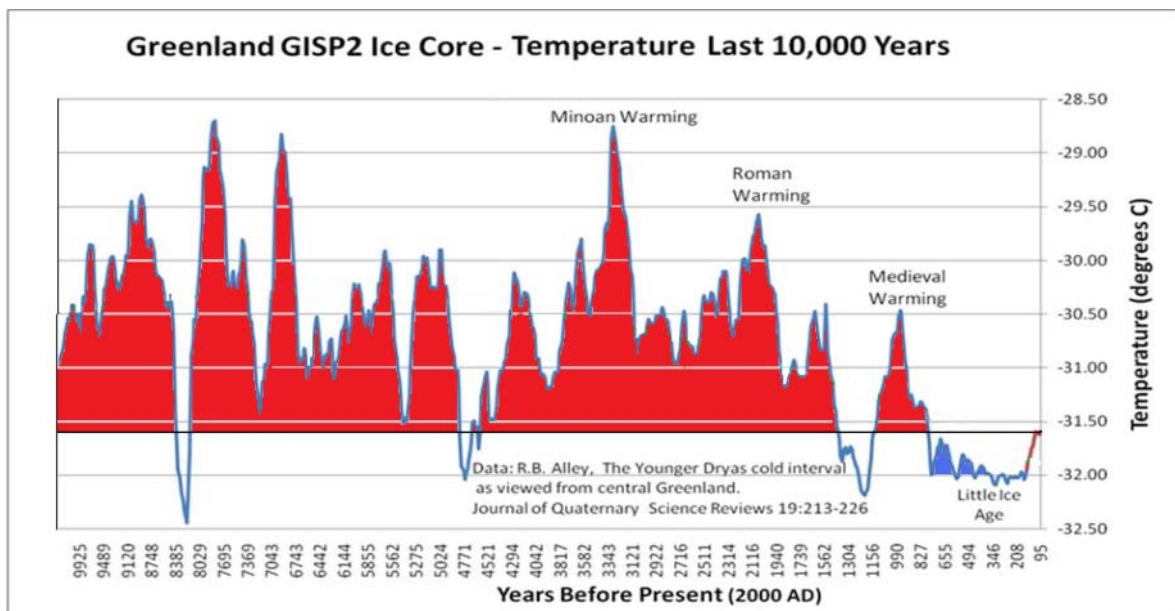


Figure 5.12.1. Temperature over the last 10,000 y from the GISP2 ice core, Greenland. Adapted from Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

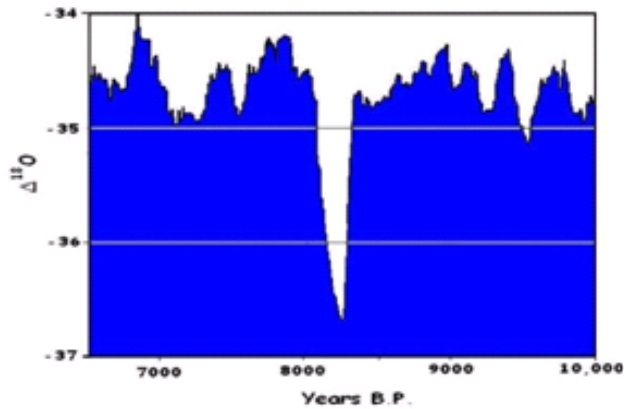


Figure 5.12.2. The 8,200 y BP sudden cooling recorded in oxygen isotope ratios in the GISP2 ice core. Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

The ensuing Dark Ages Cool Period (440–900 AD) was characterized by marked cooling again, with 540 AD marking a particularly cold year when tree rings were retarded, fruit didn't ripen, and snow fell in summer in Southern Europe. In addition, in 800 AD the Black Sea froze, and in 829 AD the Nile River froze (Oliver, 1973).

The Medieval Warm Period (900–1300 AD) that followed was marked by global temperatures warmer than at present, as indicated by the flourishing of grain crops, elevation of alpine tree lines, and building of many new towns and cities as the European population more than doubled. The Vikings took advantage of the climatic amelioration to

colonize Greenland in 985 AD, when milder climates allowed favorable open-ocean conditions for navigation and fishing. Wine grapes were grown about 500 km north of present vineyards in France and Germany, and also in the north of England (Oliver, 1973; Tkachuck, 1983). Wheat and oats were grown around Trondheim, Norway, suggesting climates about one degree C warmer than the present (Fagan, 2009).

After the Medieval Warm Period, temperatures in Europe dropped by as much as $\sim 4^{\circ}$ CC in ~ 20 years as the Little Ice Age (1300-1860 AD) commenced.

Though the overall cold lasted for 400 years, climate rhythmicity was maintained throughout, as manifest by 25 cold-warm oscillations (see Figure 5.12.3). During cold phases, the bitter winters and cool, rainy summers were too cool for satisfactory growth of cereal crops, which resulted in devastating crop failure, famine, and disease. Three years of torrential rains that began in 1315 led to the Great Famine of 1315–1317, and during colder winters the Thames River in London and canals in the Netherlands froze over (Grove, 1988, 2004; Fagan, 2001). Glaciers expanded worldwide during the Little Ice Age (Grove, 2004; Singer and Avery, 2007), with Greenland pack-ice extending well south in the North Atlantic in the thirteenth century (Singer and Avery, 2007). Glacial advances in the Swiss Alps in the mid-seventeenth century gradually encroached on farms and buried entire villages.

Elsewhere in the world, New York Harbor froze in the winter of 1780; sea ice surrounding Iceland

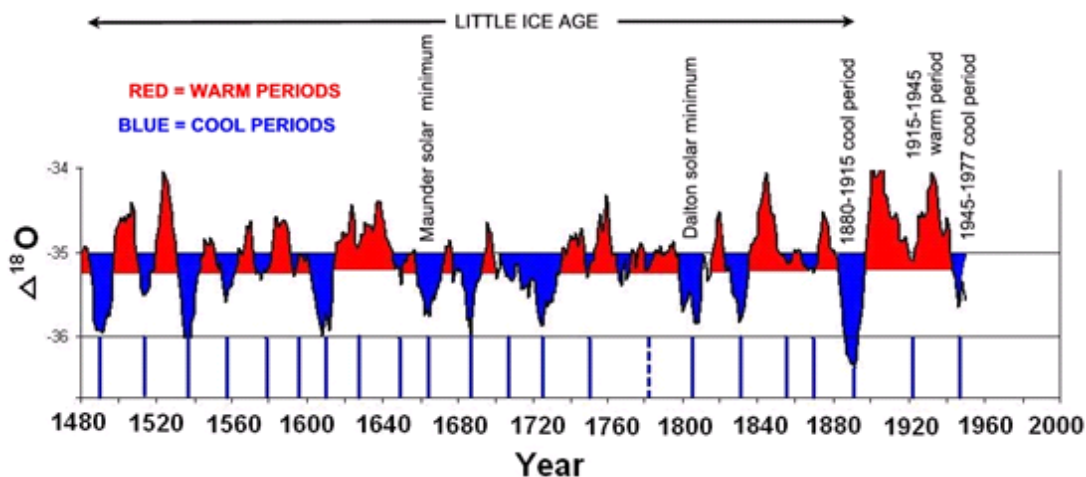


Figure 5.12.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460. Data from Grootes and Stuiver (1997). Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

extended for miles in every direction, closing many harbors; the population of Iceland decreased by half; and the Viking colonies in Greenland died out in the 1400s because food could no longer be grown there.

Conclusions

The rhythmic Holocene 1,500-year temperature changes recorded in the Greenland GISP2 ice core show the magnitude of global warming experienced during the twentieth century falls well within the bounds of previous natural variations. In addition, and especially apparent during late Holocene historical times, a multidecadal climate modulation is apparent that closely approaches the pattern observed also in the twentieth century temperature record. Because late twentieth century warming corresponded to warming limbs of both the multidecadal and the 1,500-year rhythms, it was not unexpected.

In essence, both the rate and magnitude of twentieth century warming are small compared to the magnitude of the profound natural climate reversals over the past 25,000 years (Figure 5.12.4). Most important in the context of the public debate about climate change, none of the larger late Pleistocene and Holocene climatic events were accompanied by any significant parallel change in atmospheric carbon dioxide level. The null hypothesis that twentieth century warming represents natural climate variation therefore remains valid.

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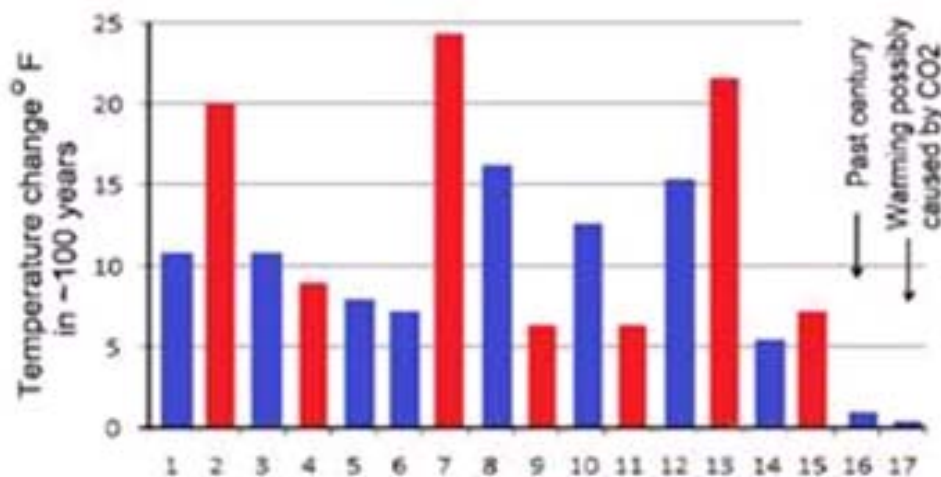


Figure 5.12.4. Magnitudes of the largest warming/cooling events over the past 25,000 years. Temperature changes shown on the vertical axis are rise or fall of temperatures in about a century. Event number 1 happened about 24,000 years ago, and event number 15 is about 11,000 years old. At least three warming events were 20 to 24 times the magnitude of warming over the past century, and four were six to nine times the magnitude of warming over the past century. The magnitude of the only modern warming which might possibly have been caused by CO₂ (1978–1998) is insignificant compared to the earlier periods of warming. Plotted from data in Cuffey and Clow (1997) and Alley (2000).

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