

Glacier Retreat

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Table of Contents

Chapter 1 - Retreat of Glaciers Since 1850

Chapter 2 - Glacier Mass Balance

Chapter 3 - Glacial Lake Outburst Flood

Chapter 4 - Holocene Glacial Retreat

Chapter 5 - Last Glacial Period

Chapter 6 - Effects of Global Warming

Chapter 7 - Global Climate Change

Chapter- 1

Retreat of Glaciers Since 1850



A view down the Whitechuck Glacier in Glacier Peak Wilderness in 1973



In a similar view as seen in 2006, where this branch of glacier retreated 1.9 kilometres (1.2 mi)

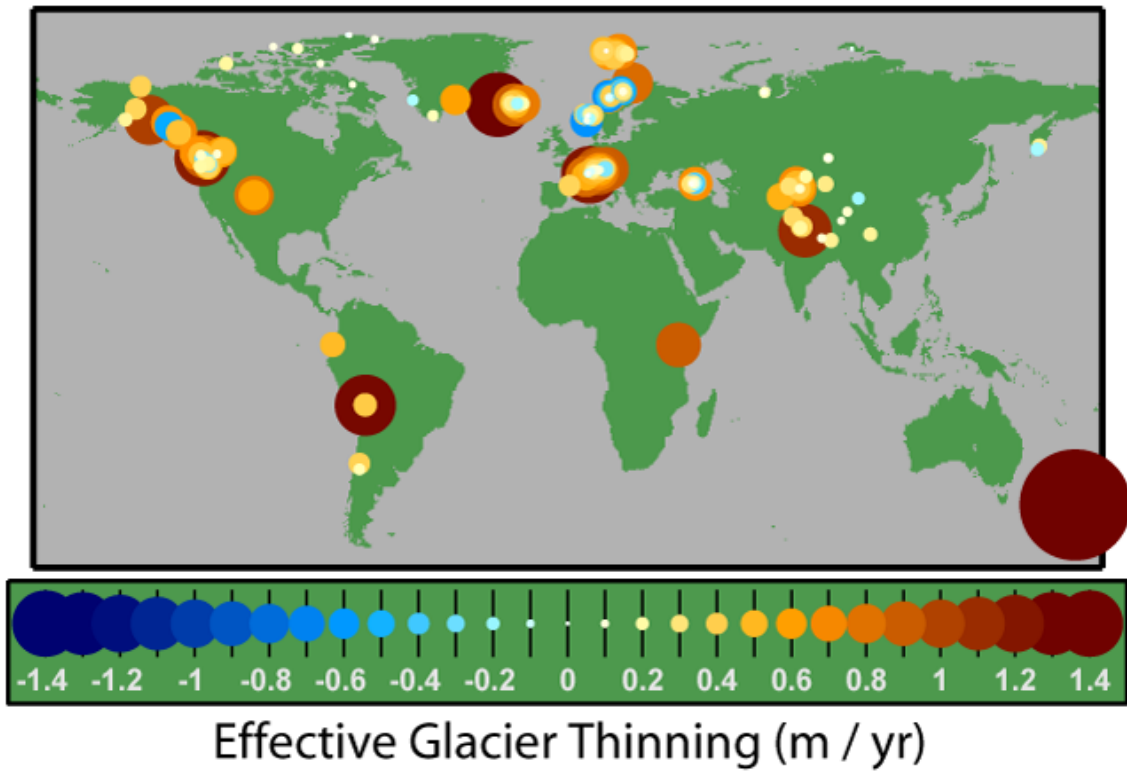
The **retreat of glaciers since 1850** affects the availability of fresh water for irrigation and domestic use, mountain recreation, animals and plants that depend on glacier-melt, and in

the longer term, the level of the oceans. Studied by glaciologists, the temporal coincidence of *glacier retreat* with the measured increase of atmospheric greenhouse gases is often cited as an evidentiary underpinning of global warming. Mid-latitude mountain ranges such as the Himalayas, Alps, Rocky Mountains, Cascade Range, and the southern Andes, as well as isolated tropical summits such as Mount Kilimanjaro in Africa, are showing some of the largest proportionate glacial loss.

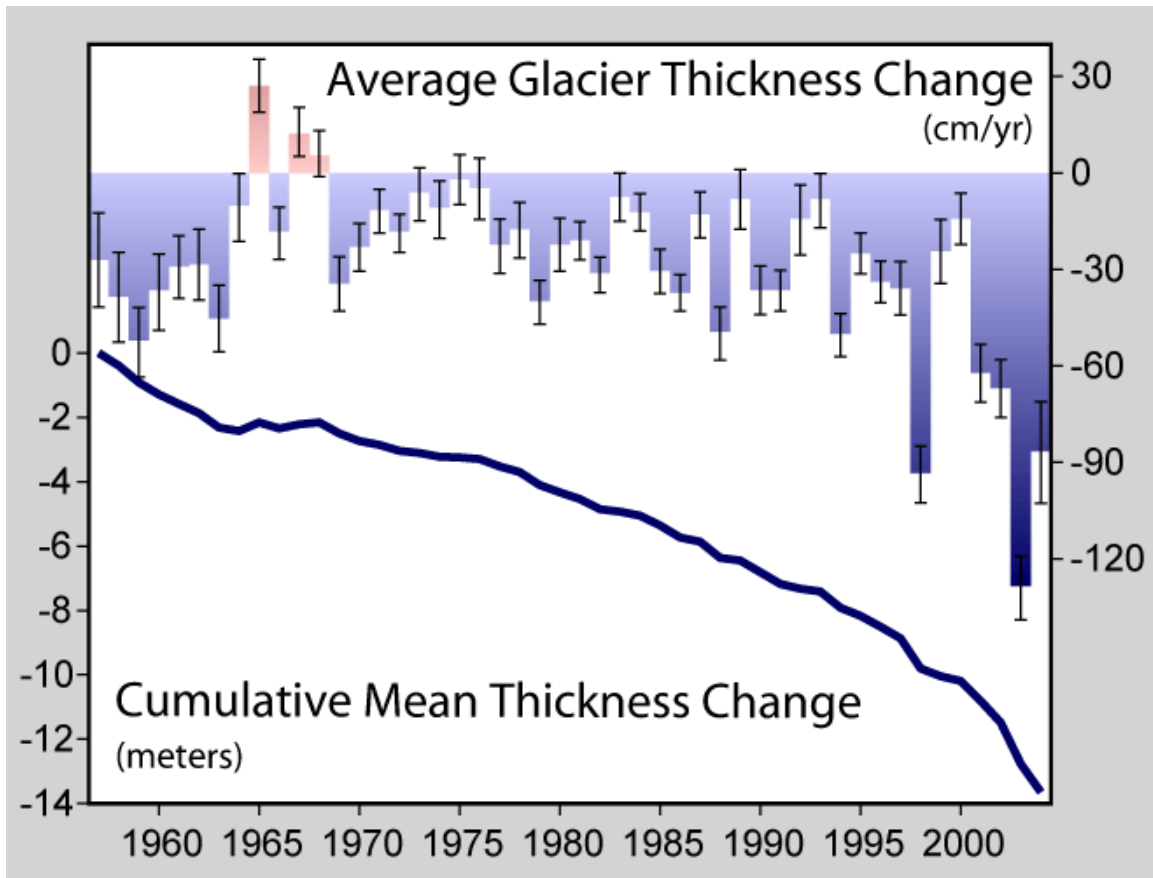
The Little Ice Age was a period from about 1550 to 1850 when the world experienced relatively cooler temperatures compared to the present. Subsequently, until about 1940, glaciers around the world retreated as the climate warmed substantially. Glacial retreat slowed and even reversed temporarily, in many cases, between 1950 and 1980 as a slight global cooling occurred. Since 1980, a significant global warming has led to glacier retreat becoming increasingly rapid and ubiquitous, so much so that some glaciers have disappeared altogether, and the existence of a great number of the remaining glaciers of the world is threatened. In locations such as the Andes of South America and Himalayas in Asia, the demise of glaciers in these regions will have potential impact on water supplies. The retreat of mountain glaciers, notably in western North America, Asia, the Alps, Indonesia and Africa, and tropical and subtropical regions of South America, has been used to provide qualitative evidence for the rise in global temperatures since the late 19th century. The recent substantial retreat and an acceleration of the rate of retreat since 1995 of a number of key outlet glaciers of the Greenland and West Antarctic ice sheets, may foreshadow a rise in sea level, having a potentially dramatic effect on coastal regions worldwide.

Glacier mass balance

Mountain Glacier Changes Since 1970



This map of mountain glacier mass balance changes since 1970 shows thinning in yellow and red, and thickening in blue.



Global glacial mass balance in the last fifty years, reported to the WGMS and NSIDC. The increasing downward trend in the late 1980s is symptomatic of the increased rate and number of retreating glaciers.

Crucial to the survival of a glacier is its mass balance, the difference between accumulation and ablation (melting and sublimation). Climate change may cause variations in both temperature and snowfall, causing changes in mass balance. A glacier with a sustained negative balance is out of equilibrium and will retreat. A glacier with sustained positive balance is also out of equilibrium, and will advance to reestablish equilibrium. Currently, there are a few advancing glaciers, although their modest growth rates suggest that they are not far from equilibrium.

Glacier retreat results in the loss of the low-elevation region of the glacier. Since higher elevations are cooler, the disappearance of the lowest portion of the glacier reduces overall ablation, thereby increasing mass balance and potentially reestablishing equilibrium. If the mass balance of a significant portion of the accumulation zone of the glacier is negative, it is in disequilibrium with the climate and will melt away without a colder climate and or an increase in frozen precipitation.

The key symptom of a glacier in disequilibrium is thinning along the entire length of the glacier. This indicates thinning in the accumulation zone. The result is marginal recession of the accumulation zone margin, not just of the terminus. In effect, the glacier no longer

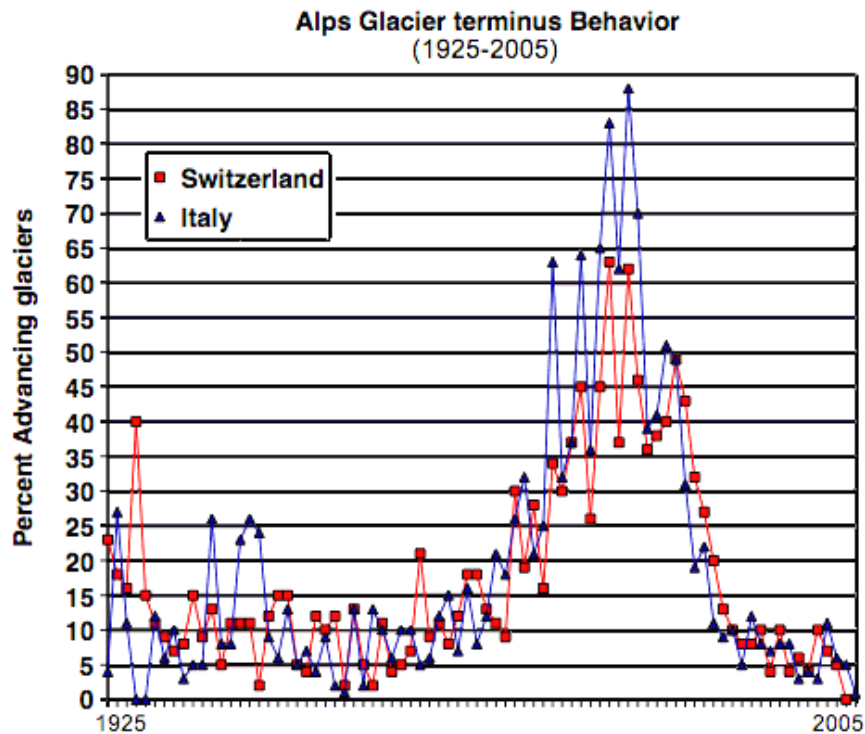
has a consistent accumulation zone and without an accumulation zone cannot survive. For example, Easton Glacier (see below) will likely shrink to half its size, but at a slowing rate of reduction, and stabilize at that size, despite the warmer temperature, over a few decades. However, the Grinnell Glacier (picture at Glacier mass balance article) will shrink at an increasing rate until it disappears. The difference is that the upper section of Easton Glacier remains healthy and snow covered, while even the upper section of the Grinnell Glacier is bare, is melting and has thinned. Small glaciers with minimal altitude range are most likely to fall into disequilibrium with the climate.

Methods for measuring glacier retreat include staking terminus location, global positioning mapping, aerial mapping, and laser altimetry.

Mid-latitude glaciers

Mid-latitude glaciers are located either between the Tropic of Cancer and the Arctic Circle, or between the Tropic of Capricorn and the Antarctic Circle. These two regions support glacier ice from mountain glaciers, valley glaciers and even smaller icecaps, which are usually located in higher mountainous regions. All of these glaciers are located in mountain ranges, notably the Himalayas; the Alps; the Pyrenees; Rocky Mountains and Pacific Coast Ranges of North America; the Patagonian Andes in South America; and mountain ranges in New Zealand. Glaciers in these latitudes are more widespread and tend to be more massive the closer they are located to the polar regions. These glaciers are the most widely studied over the past 150 years. As is true with the glaciers located in the tropical zone, virtually all the glaciers in the mid-latitudes are in a state of negative mass balance and are retreating.

Eastern hemisphere



This map from the annual Glacier Commission surveys in Italy and Switzerland shows the percentage of advancing glaciers in the Alps. Mid-20th century saw strong retreating trends, but not as extreme as the present; current retreats represent additional reductions of already smaller glaciers.

Europe

The World Glacier Monitoring Service reports on changes in the terminus, or lower elevation end, of glaciers from around the world every five years. In their 2000-2005 edition, they noted the terminal point variations of glaciers across the Alps. Over the five-year period from 2000–2005, 115 of 115 glaciers examined in Switzerland retreated, 115 of 115 glaciers in Austria retreated, in Italy during 2005 50 glaciers were retreating and 3 stationary and all 7 glaciers observed in France were in retreat. French glaciers experienced a sharp retreat in the years 1942–53 followed by advances up to 1980, and then further retreat beginning in 1982. As an example, since 1870 the Argentière Glacier and Mont Blanc Glacier have receded by 1,150 m (3,770 ft) and 1,400 m (4,600 ft), respectively. The largest glacier in France, the Mer de Glace, which is 11 km (6.8 mi) long and 400 m (1,300 ft) thick, has lost 8.3% of its length, or 1 km (0.62 mi), in 130 years, and thinned by 27%, or 150 m (490 ft), in the midsection of the glacier since 1907. The Bossons Glacier in Chamonix, France, has retreated 1,200 m (3,900 ft) from extents observed in the early 20th century. In 2005, of 91 Swiss glaciers studied, 84 retreated from where their terminal points had been in 2004 while the remaining 7 showed no change.

Other researchers have found that glaciers across the Alps appear to be retreating at a faster rate than a few decades ago. In 2008, the Swiss Glacier survey of 85 glaciers found 78 retreating, 2 stationary and 5 advancing. The Trift Glacier had retreated over 500 m (1,600 ft) just in the three years of 2003 to 2005, which is 10% of its total length. The Grosser Aletsch Glacier, the largest glacier in Switzerland, has retreated 2,600 m (8,500 ft) since 1880. This rate of retreat has also increased since 1980, with 30%, or 800 m (2,600 ft), of the total retreat occurring in the last 20% of the time period. Similarly, of the glaciers in the Italian Alps, only about a third were in retreat in 1980, while by 1999, 89% of these glaciers were retreating. In 2005, the Italian Glacier Commission found that 123 glaciers were retreating, 1 advancing and 6 stationary. Repeat photography of glaciers in the Alps provides clear evidence that glaciers in this region have retreated significantly in the past several decades. Morteratsch Glacier, Switzerland is one key example. The yearly measurements of the length changes started in 1878. The overall retreat from 1878 to 1998 has been 2 km (1.2 mi) with a mean annual retreat rate of approximately 17 m (56 ft) per year. This long-term average was markedly surpassed in recent years with the glacier receding 30 m (98 ft) per year during the period between 1999–2005. One major concern which has in the past had great impact on lives and property is the death and destruction from a Glacial Lake Outburst Flood (GLOF). Glaciers stockpile rock and soil that has been carved from mountainsides at their terminal end. These debris piles often form dams that impound water behind them and form glacial lakes as the glaciers melt and retreat from their maximum extents. These terminal moraines are frequently unstable and have been known to burst if overfilled or displaced by earthquakes, landslides or avalanches. If a glacier has a rapid melting cycle during warmer months, the terminal moraine may not be strong enough to hold the rising water behind it, leading to a massive localized flood. This is an increasing risk due to the creation and expansion of glacial lakes resulting from glacier retreat. Past floods have been deadly and have resulted in enormous property damage. Towns and villages in steep, narrow valleys that are downstream from glacial lakes are at the greatest risk. In 1892 a GLOF released some 200,000 km³ (2.6×10^{14} cu yd) of water from the lake of the Glacier de Tête Rousse, resulting in the deaths of 200 people in the French town of Saint Gervais. GLOFs have been known to occur in every region of the world where glaciers are located. Continued glacier retreat is expected to create and expand glacial lakes, increasing the danger of future GLOFs.

Though the glaciers of the Alps have received more attention from glaciologists than in other areas of Europe, research indicates that throughout most of Europe, glaciers are rapidly retreating. In the Kebnekaise Mountains of northern Sweden, a study of 16 glaciers between 1990 and 2001 found that 14 glaciers were retreating, one was advancing and one was stable. During the 20th century, glaciers in Norway retreated overall with brief periods of advance around 1910, 1925 and in the 1990s. In the 1990s, 11 of 25 Norwegian glaciers observed had advanced due to several consecutive winters with above normal precipitation. However, following several consecutive years of little winter precipitation since 2000, and record warmth during the summers of 2002 and 2003, Norwegian glaciers have decreased significantly since the 1990s. By 2005 only 1 of the 25 glaciers monitored in Norway was advancing, two were stationary and 22 were retreating. In 2009 18 glaciers retreated, three were stationary (less than 2 meters of

change) and two advanced. In 2006 glacier mass balances were very negative in Norway and of the 26 glaciers examined, 24 were retreating with one stationary and one advancing. The Norwegian Engabreen Glacier has retreated 185 m (607 ft) since 1999, while the Brenndalsbreen and Rembesdalskkåka glaciers have retreated 276 m (906 ft) and 250 m (820 ft), respectively, since 2000. The Briksdalsbreen glacier retreated 96 m (315 ft) in 2004 alone—the largest annual retreat recorded for this glacier since monitoring began in 1900. This figure was exceeded in 2006 with five glaciers retreating over 100 m (330 ft) from the fall of 2005 to the fall of 2006. Four outlets from the Jostedalbreen ice cap, Kjenndalsbreen, Brenndalsbreen, Briksdalsbreen and Bergsetbreen had a frontal retreat of more than 100 metres. Gråfjellsbreen, an outlet from Folgefonna, had a retreat of almost 100 m (330 ft). Overall, from 1999 to 2005, Briksdalsbreen retreated 336 metres (1,102 ft).

In the Spanish Pyrenees, recent studies have shown important losses in extent and volume of the glaciers of the Maladeta massif during the period 1981-2005. These include a reduction in area of 35.7%, from 2.41 km² (600 acres) to .627 km² (155 acres), a loss in total ice volume of .0137 km³ (0.0033 cu mi) and an increase in the mean altitude of the glacial termini of 43.5 m (143 ft). For the Pyrenees as a whole 50-60% of the glaciated area has been lost since 1991. At least three glaciers Balaitus, Perdiguero and La Munia have disappeared in this period. Monte Perdido Glacier has shrunk from 90 hectares to 40 hectares.

Siberia

Siberia and the Russian Far East, although typically classified as polar regions, owing to the dryness of the winter climate have glaciers only in the high Altai Mountains, Verkhoyansk Range and Cherskiy Range. Kamchatka, exposed to moisture from the Sea of Okhotsk, has much more extensive glaciation totaling around 2,500 square kilometres (970 square miles).

Because the collapse of Communism has caused a large reduction in the number of monitoring stations, details on the retreat of Siberian glaciers is much poorer than in most other regions of the world. Nonetheless, available records do indicate a general retreat of all glaciers in the Altai Mountains and (with the exception of volcanic glaciers) in Kamchatka. Sakha's glaciers, totaling seventy square kilometers, have shrunk by around 28% since 1945, whilst in moister regions of Siberia and on the Pacific coast, the shrinkage is considerably larger, reaching several percent annually in some places.

Asia



This NASA image shows the formation of numerous glacial lakes at the termini of receding glaciers in Bhutan-Himalaya.

The Himalayas and other mountain chains of central Asia support large regions that are glaciated. These glaciers provide critical water supplies to arid countries such as Mongolia, western China, Pakistan, Afghanistan and India. As is true with other glaciers worldwide, the glaciers of Asia are experiencing a rapid decline in mass. The loss of these glaciers would have a tremendous impact on the ecosystem of the region.

In the Wakhan Corridor of Afghanistan 28 of 30 glaciers examined retreated significantly during the 1976-2003 period, the average retreat was 11 meters per year. One of these glaciers, the Zemestan Glacier, has retreated 460 m during this period, not quite 10% of its 5.2 km length. In examining 612 glaciers in China between 1950 and 1970, 53% of the glaciers studied were retreating. After 1990, 95% of these glaciers were measured to be retreating, indicating that retreat of these glaciers was becoming more widespread. Glaciers in the Mount Everest region of the Himalayas are all in a state of retreat. The Rongbuk Glacier, draining the north side of Mount Everest into Tibet, has been retreating 20 m (66 ft) per year. In the Khumbu region of Nepal along the front of the main Himalaya of 15 glaciers examined from 1976-2007 all retreated significantly, average retreat was 28 m per year. The most famous of these Khumbu Glacier retreated at a rate of 18 m per year from 1976-2007. In India the Gangotri Glacier, retreated 34 m (112 ft) per year between 1970 and 1996, and has averaged a loss of 30 m (98 ft) per year since 2000. However, the glacier is still over 30 km (19 mi) long. In 2005 the Tehri Dam was finished on the Bhagirathi River, it is a 2400 mW facility that began producing hydropower in 2006. The headwaters of the Bhagirathi River is the Gangotri and Khatling Glacier, Garhwal Himalaya. Gangotri Glacier has retreated 1 km in the last 30 years, and with an area of 286 km² provides up to 190 m³/second (Singh et al., 2006).

For the Indian Himalaya retreat ranged from -19 meters per year for 17 glaciers all retreating. In Sikkim 26 glaciers examined were retreating at an average rate of 13.02 m per year from 1976 to 2005. For the 51 glaciers in the main Himalayan Range of India, Nepal and Sikkim 51 are retreating, at an average rate of 23 m per year. In the Karokoram Range of the Himalaya there is a mix of advancing and retreating glaciers with 18 advancing and 22 retreating during the 1980-2003 period. Many of the advancing Karakoram glaciers are surging.

With the retreat of glaciers in the Himalayas, a number of glacial lakes have been created. A growing concern is the potential for Glacial Lake Outburst Floods—researchers estimate 20 glacial lakes in Nepal and 24 in Bhutan pose hazards to human populations should their terminal moraine dams fail. One glacial lake identified as potentially hazardous is Bhutan's Raphstreng Tsho, which measured 1.6 km (0.99 mi) long, .96 m (0.00096 km) wide and was 80 m (260 ft) deep in 1986. By 1995 the lake had swollen to a length of 1.94 km (1.21 mi), 1.13 km (0.70 mi) in width and a depth of 107 m (351 ft). In 1994 a GLOF from Luggye Tsho, a glacial lake adjacent to Raphstreng Tsho, killed 23 people downstream.

Glaciers in the Ak-shirak Range in Kyrgyzstan experienced a slight loss between 1943 and 1977 and an accelerated loss of 20% of their remaining mass between 1977 and 2001. In the Tien Shan mountains, which Kyrgyzstan shares with China and Kazakhstan, studies in the northern areas of that mountain range show that the glaciers that help supply water to this arid region have been losing nearly 2 km³ (0.48 cu mi) of ice per year between 1955 and 2000. The University of Oxford study also reported that an average of 1.28% of the volume of these glaciers had been lost per year between 1974 and 1990.

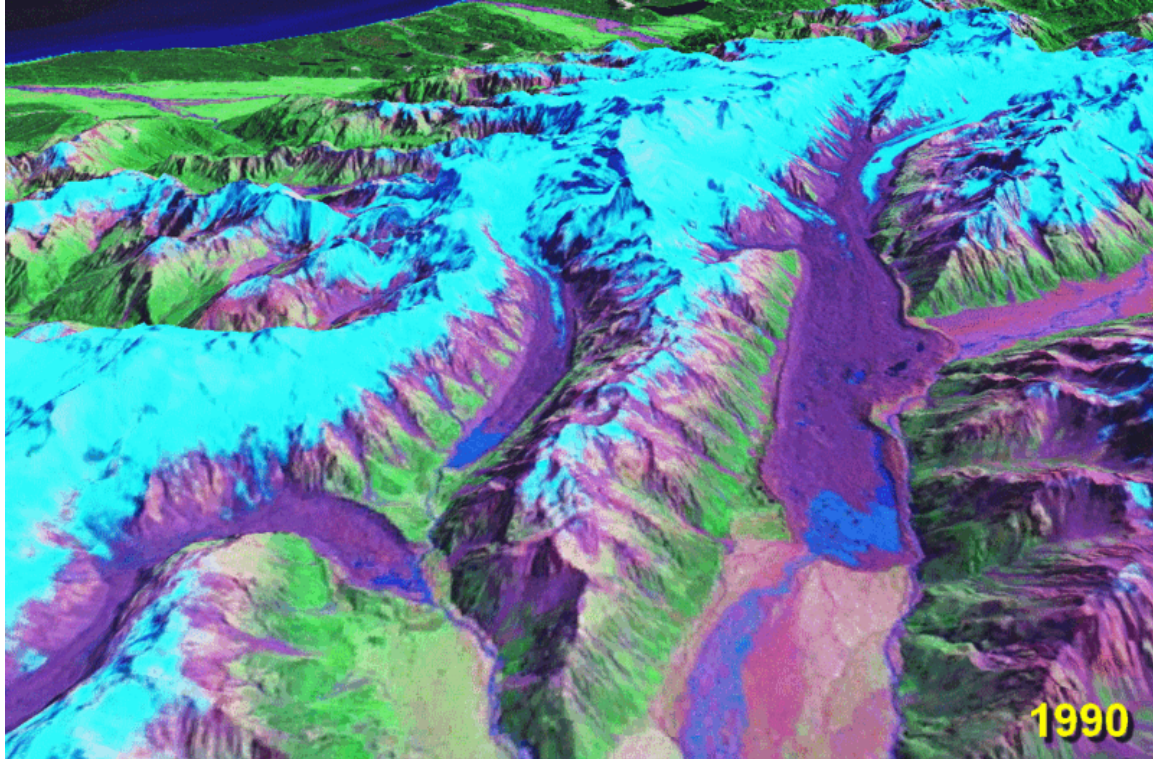
To the south of the Tien Shan, the Pamirs mountain range located primarily in Tajikistan has many thousands of glaciers, all of which are in a general state of retreat. During the 20th century, the glaciers of Tajikistan lost 20 km³ (4.8 cu mi) of ice. The 70 km (43 mi) long Fedchenko Glacier, which is the largest in Tajikistan and the largest non-polar glacier on Earth, lost 1.4% of its length, or 1 km (0.62 mi), 2 km³ (0.48 cu mi) of its mass, and the glaciated area was reduced by 11 km² (4.2 sq mi) during the 20th century. Similarly, the neighboring Skogatch Glacier lost 8% of its total mass between 1969 and 1986. The country of Tajikistan and neighboring countries of the Pamir Range are highly dependent upon glacial runoff to ensure river flow during droughts and the dry seasons experienced every year. The continued demise of glacier ice will result in a short-term increase, followed by a long-term decrease in glacial melt water flowing into rivers and streams.

The Tibetan Plateau contains the world's third-largest store of ice. Qin Dahe, the former head of the China Meteorological Administration, said that the recent fast pace of melting and warmer temperatures will be good for agriculture and tourism in the short term; but issued a strong warning:

"Temperatures are rising four times faster than elsewhere in China, and the Tibetan glaciers are retreating at a higher speed than in any other part of the world.... In the short

term, this will cause lakes to expand and bring floods and mudflows. . . . In the long run, the glaciers are vital lifelines for Asian rivers, including the Indus and the Ganges. Once they vanish, water supplies in those regions will be in peril."

Oceania



These glaciers in New Zealand have continued to retreat rapidly in recent years. Notice the larger terminal lakes, the retreat of the white ice (ice free of moraine cover), and the higher moraine walls due to ice thinning.

In New Zealand the mountain glaciers have been in general retreat since 1890, with an acceleration of this retreat since 1920. Most of the glaciers have thinned measurably and have reduced in size, and the snow accumulation zones have risen in elevation as the 20th century progressed. During the period 1971–75, Ivory Glacier receded 30 m (98 ft) from the glacial terminus, and about 26% of the surface area of the glacier was lost over the same period. Since 1980 numerous small glacial lakes were created behind the new terminal moraines of several of these glaciers. Glaciers such as Classen, Godley and Douglas now all have new glacial lakes below their terminal locations due to the glacial retreat over the past 20 years. Satellite imagery indicates that these lakes are continuing to expand. There has been significant and ongoing ice volume losses on the largest New Zealand glaciers, including the Tasman, Ivory, Classen, Mueller, Maud, Hooker, Grey, Godley, Ramsay, Murchison, Therma, Volta and Douglas Glaciers. The retreat of these glaciers has been marked by expanding proglacial lakes and terminus region thinning. The loss in volume from 1975-2005 is 11% of the total.

Several glaciers, notably the much-visited Fox and Franz Josef Glaciers on New Zealand's West Coast, have periodically advanced, especially during the 1990s, but the scale of these advances is small when compared to 20th-century retreat. Both glaciers are currently more than 2.5 km (1.6 mi) shorter than a century ago. These large, rapidly flowing glaciers situated on steep slopes have been very reactive to small mass-balance changes. A few years of conditions favorable to glacier advance, such as more westerly winds and a resulting increase in snowfall, are rapidly echoed in a corresponding advance, followed by equally rapid retreat when those favorable conditions end. The glaciers that have been advancing in a few locations in New Zealand have been doing so due to a temporary weather change associated with El Niño, which has brought more precipitation and cloudier, cooler summers since 2002.

Western hemisphere

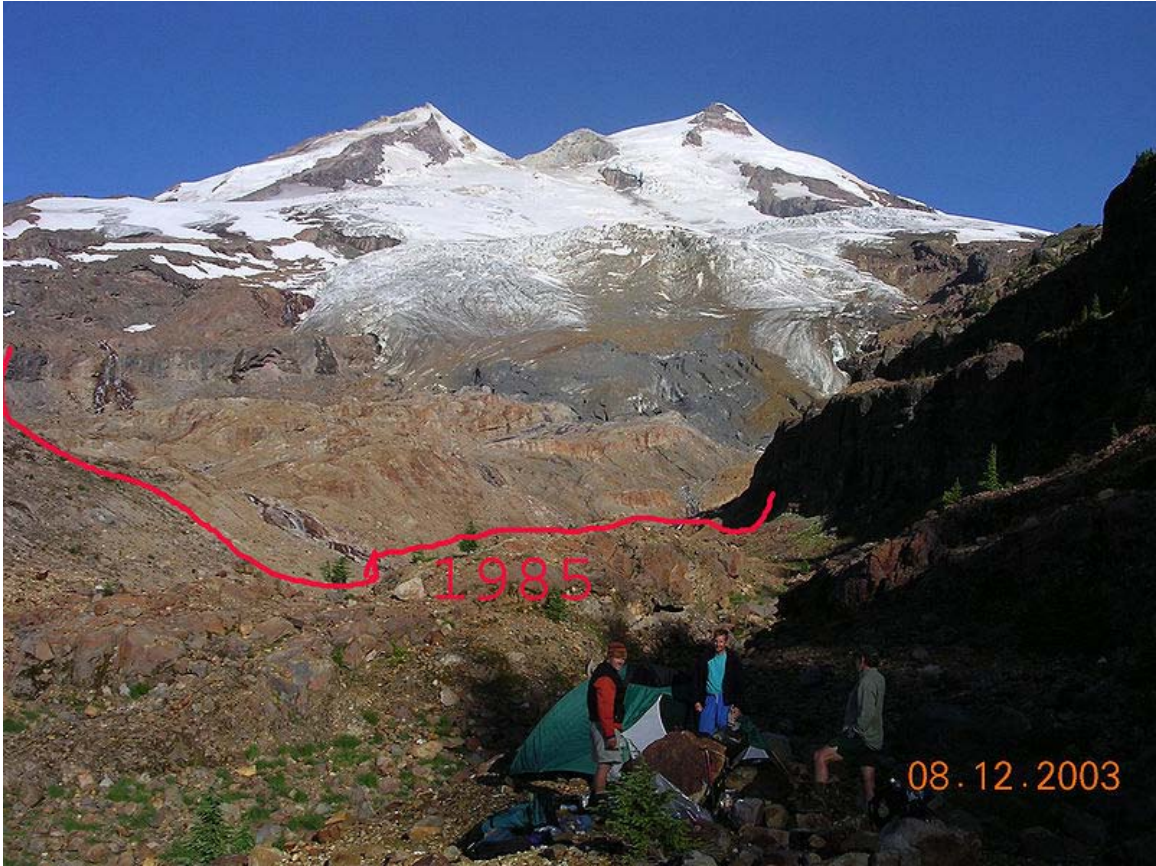


The Lewis Glacier, North Cascades National Park after melting away in 1990

North American glaciers are primarily located along the spine of the Rocky Mountains in the United States and Canada, and the Pacific Coast Ranges extending from northern California to Alaska. While Greenland is geologically associated with North America, it is also a part of the Arctic region. Apart from the few tidewater glaciers such as Taku Glacier, that are in the advance stage of their tidewater glacier cycle prevalent along the coast of Alaska, virtually all the glaciers of North America are in a state of retreat. The observed retreat rate has increased rapidly since approximately 1980, and overall each decade since has seen greater rates of retreat than the preceding one. There are also small remnant glaciers scattered throughout the Sierra Nevada mountains of California and Nevada.

Cascades

The Cascade Range of western North America extends from southern British Columbia in Canada to northern California. Excepting Alaska, about half of the glacial area in the U.S. is contained in the more than 700 glaciers of the North Cascades, a portion of the range between the Canadian border and I-90 in central Washington. These glaciers store as much water as that contained in all the lakes and reservoirs in the rest of the state, and provide much of the stream and river flow in the dry summer months, approximating some 870,000 m³ (1,140,000 cu yd).



The Boulder Glacier retreated 450 m (1,480 ft) from 1987 to 2005



The Easton Glacier retreated 255 m (837 ft) from 1990 to 2005

As recently as 1975, many North Cascade glaciers were advancing due to cooler weather and increased precipitation that occurred from 1944 to 1976. However, by 1987 all the North Cascade glaciers were retreating, and the pace of the glacier retreat has increased each decade since the mid-1970s. Between 1984 and 2005, the North Cascade glaciers lost an average of more than 12.5 m in thickness and between 20% and 40% of their volume.

Glaciologists researching the North Cascades glaciers have found that all 47 monitored glaciers are receding and that four glaciers—Spider Glacier, Lewis Glacier (pictured), Milk Lake Glacier, and David Glacier—have disappeared completely since 1985. The White Chuck Glacier (near Glacier Peak) is a particularly dramatic example. The glacier area shrank from 3.1 km² (1.2 sq mi) in 1958 to .9 km² (0.35 sq mi) by 2002. Between 1850 and 1950, the Boulder Glacier on the southeast flank of Mount Baker retreated 8,700 feet (2,650 m). William Long of the United States Forest Service observed the glacier beginning to advance due to cooler/wetter weather in 1953. This was followed by a 2,438 feet (743 m) advance by 1979. The glacier again retreated 450 m (1,480 ft) from 1987 to 2005, leaving barren terrain behind. This retreat has occurred during a period of reduced winter snowfall and higher summer temperatures. In this region of the Cascades, winter snowpack has declined 25% since 1946, and summer temperatures have risen 0.7 °C (1.2 °F) during the same period. The reduced snowpack has occurred despite a

small increase in winter precipitation; thus, it reflects warmer winter temperatures leading to rainfall and melting on glaciers even during the winter. As of 2005, 67% of the North Cascade glaciers observed are in disequilibrium and will not survive the continuation of the present climate. These glaciers will eventually disappear unless temperatures fall and frozen precipitation increases. The remaining glaciers are expected to stabilize, unless the climate continues to warm, but will be much reduced in size.

U.S. Rocky Mountains

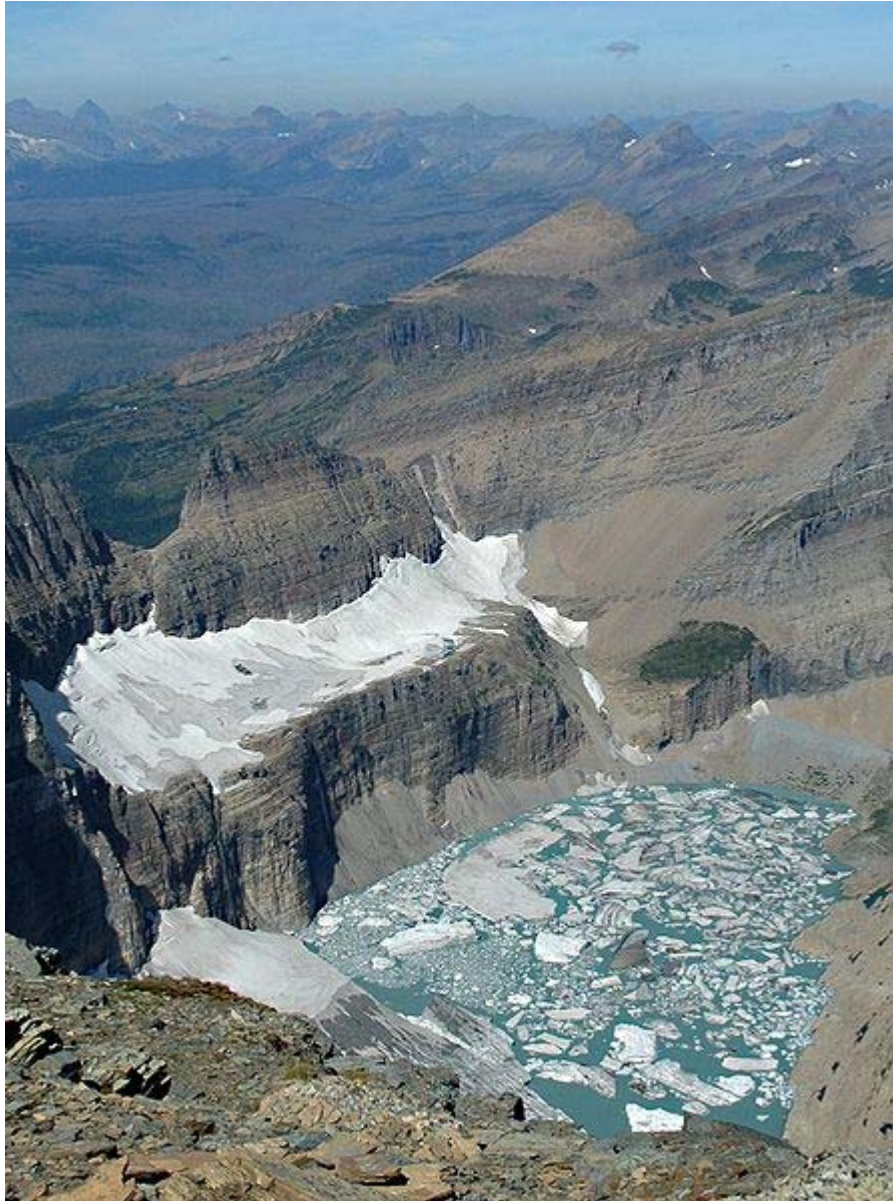
On the sheltered slopes of the highest peaks of Glacier National Park in Montana, its eponymous glaciers are diminishing rapidly. The area of each glacier has been mapped by the National Park Service and the U.S. Geological Survey for decades. Comparing photographs taken in the mid-19th century with contemporary images provides ample evidence that the glaciers in the park have retreated notably since 1850. Repeat photography over the decades since clearly show that glaciers throughout the park such as Grinnell Glacier are all retreating. The larger glaciers are now approximately a third of their former size when first studied in 1850, and numerous smaller glaciers have disappeared completely. Only 27% of the 99 km² (38 sq mi) area of Glacier National Park covered by glaciers in 1850 remained covered by 1993. Researchers believe that by the year 2030, the vast majority of glacial ice in Glacier National Park will be gone unless current climate patterns reverse their course. Grinnell Glacier is just one of many glaciers in Glacier National Park that have been well documented by photographs for many decades. The photographs below clearly demonstrate the retreat of this glacier since 1938.



1938 *T.J. Hileman GNP*



1981 *Carl Key (USGS)*



2009 *Lindsey Bengtson (USGS)*

The semiarid climate of Wyoming still manages to support about a dozen small glaciers within Grand Teton National Park, which all show evidence of retreat over the past 50 years. Schoolroom Glacier, located slightly southwest of Grand Teton, one of the more easily reached glaciers in the park, is expected to disappear by 2025. Research between 1950 and 1999 demonstrated that the glaciers in Bridger-Teton National Forest and Shoshone National Forest in the Wind River Range shrank by over a third of their size during that period. Photographs indicate that the glaciers today are only half the size as when first photographed in the late 1890s. Research also indicates that the glacial retreat was proportionately greater in the 1990s than in any other decade over the last 100 years. Gannett Glacier on the northeast slope of Gannett Peak is the largest single glacier in the Rocky Mountains south of Canada. It has reportedly lost over 50% of its volume since

1920, with almost half of that loss occurring since 1980. Glaciologists believe the remaining glaciers in Wyoming will disappear by the middle of the 21st century if the current climate patterns continue.

Canadian Rockies and British Columbia Coast Range



Fast-melting toe of the Athabasca Glacier, 2005



The Athabasca Glacier in the Columbia Icefield of the Canadian Rockies, has retreated 1,500 m in the last century.



Valdez Glacier has thinned 90 m (300 ft) over the last century and the barren ground near the glacial margins have been exposed due to the glacier thinning and retreating over the last two decades of the 20th century.

In the Canadian Rockies, the glaciers are generally larger and more widespread than they are to the south in the United States Rocky Mountains. One of the more accessible glaciers in the Canadian Rockies is the Athabasca Glacier, which is an outlet glacier of the 325 km² (125 sq mi) Columbia Icefield. The Athabasca Glacier has retreated 1,500 m (4,900 ft) since the late 19th century. The rate of retreat for this glacier has increased since 1980, following a period of slow retreat from 1950 to 1980. The Peyto Glacier in Alberta covers an area of about 12 km² (4.6 sq mi), and retreated rapidly during the first half of the 20th century, stabilized by 1966, and resumed shrinking in 1976. Illecillewaet Glacier in British Columbia's Glacier National Park (Canada) has retreated 2 km (1.2 mi) since first photographed in 1887.

In Garibaldi Provincial park in SW British Columbia over 505 km², or 26%, of the park, was covered by glacier ice at the beginning of the 18th century. Ice cover decreased to 297 km² by 1987–1988 and to 245 km² by 2005, 50% of the 1850 area. The 50 km² loss in the last 20 years coincides with negative mass balance in the region. During this period all nine glaciers examined have retreated significantly.

Alaska

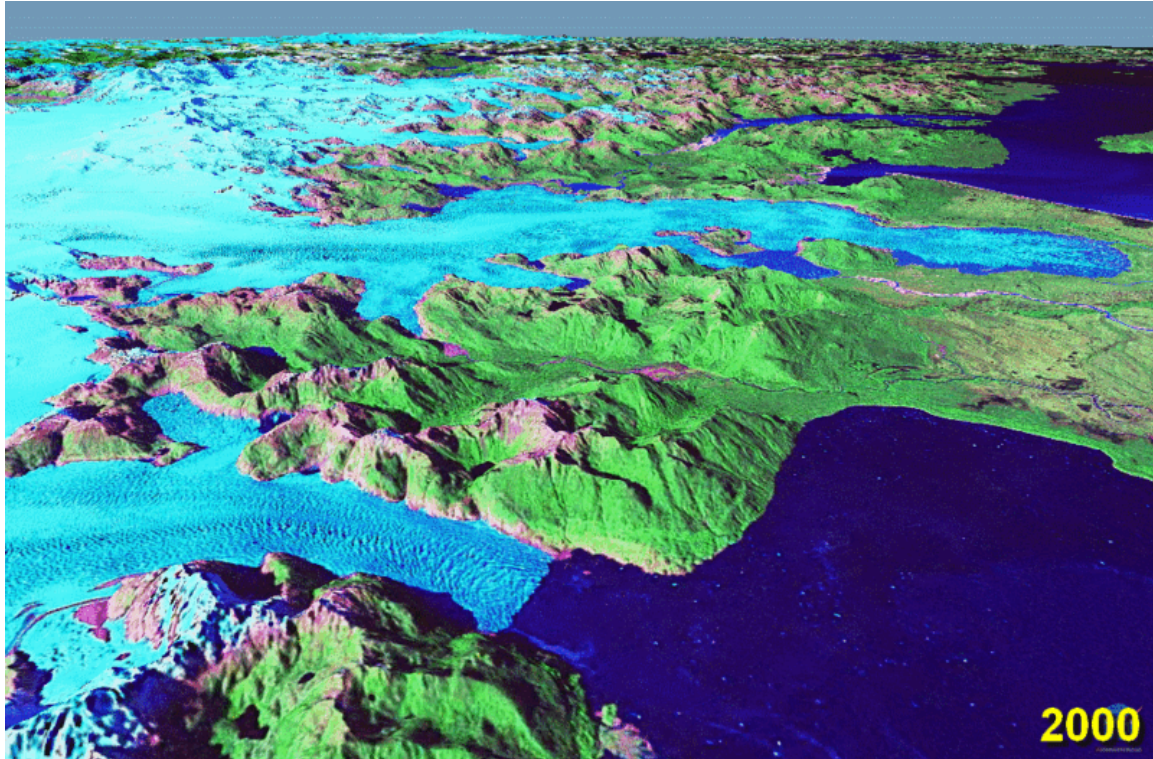
There are thousands of glaciers in Alaska, though only a relative few of them have been named. The Columbia Glacier near Valdez in Prince William Sound has retreated 15 km (9.3 mi) in the last 25 years. Icebergs calved off this glacier were a partial cause of the Exxon Valdez oil spill, as the oil tanker had changed course to avoid the icebergs. The Valdez Glacier is in the same area, and though it does not calve, it has also retreated significantly. "A 2005 aerial survey of Alaskan coastal glaciers identified more than a dozen glaciers, many former tidewater and calving glaciers, including Grand Plateau, Alesk, Bear, and Excelsior Glaciers that are rapidly retreating. Of 2,000 glaciers observed, 99% are retreating." Icy Bay in Alaska is fed by three large glaciers—Guyot, Yahtse, and Tyndall Glaciers—all of which have experienced a loss in length and thickness and, consequently, a loss in area. Tyndall Glacier became separated from the retreating Guyot Glacier in the 1960s and has retreated 24 km (15 mi) since, averaging more than 500 m (1,600 ft) per year.

The Juneau Icefield Research Program has monitored the outlet glaciers of the Juneau Icefield since 1946. On the west side of the ice field, the terminus of the Mendenhall Glacier, which flows into suburban Juneau, Alaska, has retreated 580 m (1,900 ft). Of the nineteen glaciers of the Juneau Icefield, eighteen are retreating, and one, the Taku Glacier, is advancing. Eleven of the glaciers have retreated more than 1 km (0.62 mi) since 1948 — Antler Glacier, 5.4 km (3.4 mi); Gilkey Glacier, 3.5 km (2.2 mi); Norris Glacier, 1.1 km (0.68 mi) and Lemon Creek Glacier, 1.5 km (0.93 mi). Taku Glacier has been advancing since at least 1890, when naturalist John Muir observed a large iceberg calving front. By 1948 the adjacent fjord had filled in, and the glacier no longer calved and was able to continue its advance. By 2005 the glacier was only 1.5 km (0.93 mi) from reaching Taku Point and blocking Taku Inlet. The advance of Taku Glacier averaged 17 m (56 ft) per year between 1988 and 2005. The mass balance was very positive for the 1946–88 period fueling the advance; however, since 1988 the mass balance has been slightly negative, which should in the future slow the advance of this mighty glacier.

Long-term mass balance records from Lemon Creek Glacier in Alaska show slightly declining mass balance with time. The mean annual balance for this glacier was -0.23 m (0.75 ft) each year during the period of 1957 to 1976. Mean annual balance has been increasingly negatively averaging -1.04 m (3.4 ft) per year from 1990 to 2005. Repeat glacier altimetry, or altitude measuring, for 67 Alaska glaciers find rates of thinning have increased by more than a factor of two when comparing the periods from 1950 to 1995 (0.7 m (2.3 ft) per year) and 1995 to 2001 (1.8 m (5.9 ft) per year). This is a systemic trend with loss in mass equating to loss in thickness, which leads to increasing retreat—the glaciers are not only retreating, but they are also becoming much thinner. In Denali National Park, all glaciers monitored are retreating, with an average retreat of 20 m (66 ft) per year. The terminus of the Toklat Glacier has been retreating 26 m (85 ft) per year and the Muldrow Glacier has thinned 20 m (66 ft) since 1979. Well documented in Alaska are surging glaciers that have been known to rapidly advance, even as much as 100 m (330 ft) per day. Variegated, Black Rapids, Muldrow, Susitna and Yanert are

examples of surging glaciers in Alaska that have made rapid advances in the past. These glaciers are all retreating overall, punctuated by short periods of advance.

Andes and Tierra del Fuego



Retreat of San Rafael Glacier from 1990 to 2000. San Quintín Glacier is shown in the background

A large region of population surrounding the central and southern Andes of Argentina and Chile reside in arid areas that are dependent on water supplies from melting glaciers. The water from the glaciers also supplies rivers that have in some cases been dammed for hydroelectric power. Some researchers believe that by 2030, many of the large ice caps on the highest Andes will be gone if current climate trends continue. In Patagonia on the southern tip of the continent, the large ice caps have retreated a 1 km (0.62 mi) since the early 1990s and 10 km (6.2 mi) since the late 19th century. It has also been observed that Patagonian glaciers are receding at a faster rate than in any other world region. The Northern Patagonian Ice Field lost 93 km² (36 sq mi) of glacier area during the years between 1945 and 1975, and 174 km² (67 sq mi) from 1975 to 1996, which indicates that the rate of retreat is increasing. This represents a loss of 8% of the ice field, with all glaciers experiencing significant retreat. The Southern Patagonian Ice Field has exhibited a general trend of retreat on 42 glaciers, while four glaciers were in equilibrium and two advanced during the years between 1944 and 1986. The largest retreat was on O'Higgins Glacier, which during the period 1896–1995 retreated 14.6 km (9.1 mi). The Perito Moreno Glacier is 30 km (19 mi) long and is a major outflow glacier of the Patagonian ice sheet, as well as the most visited glacier in Patagonia. Perito Moreno Glacier is

presently in equilibrium, but has undergone frequent oscillations in the period 1947–96, with a net gain of 4.1 km (2.5 mi). This glacier has advanced since 1947, and has been essentially stable since 1992. Perito Moreno Glacier is one of three glaciers in Patagonia known to have advanced, compared to several hundred others in retreat. The two major glaciers of the Southern Patagonia Icefield to the north of Moreno, Upsala and Videma Glacier have retreated 4.6 km (2.9 mi) in 21 years and 1 km (0.62 mi) in 13 years respectively. In the Aconcagua River Basin, glacier retreat has resulted in a 20% loss in glacier area, declining from 151 km² (58 sq mi) to 121 km² (47 sq mi). The Marinelli Glacier in Tierra del Fuego has been in retreat since at least 1960 through 2008.

Tropical glaciers

Tropical glaciers are located between the Tropic of Cancer and the Tropic of Capricorn, in the region that lies 23° 26' 22" north or south of the equator. Tropical glaciers are the most uncommon of all glaciers for a variety of reasons. Firstly, the tropics are the warmest part of the planet. Secondly, the seasonal change is minimal with temperatures warm year round, resulting in a lack of a colder winter season in which snow and ice can accumulate. Thirdly, few taller mountains exist in these regions upon which enough cold air exists for the establishment of glaciers. All of the glaciers located in the tropics are on isolated high mountain peaks. Overall, tropical glaciers are smaller than those found elsewhere and are the most likely glaciers to show rapid response to changing climate patterns. A small temperature increase of only a few degrees can have almost immediate and adverse impact on tropical glaciers.

Africa



Furtwängler Glacier atop Kilimanjaro in the foreground and snowfields and the Northern Icefields beyond.

With almost the entire continent of Africa located in the tropical and subtropical climate zones, glaciers are restricted to two isolated peaks and the Ruwenzori Range. Kilimanjaro, at 5,895 m (19,341 ft), is the highest peak on the continent. Since 1912 the glacier cover on the summit of Kilimanjaro has apparently retreated 75%, and the volume of glacial ice is now 80% less than it was a century ago due to both retreat and thinning. In the 14-year period from 1984 to 1998, one section of the glacier atop the mountain receded 300 m (980 ft). A 2002 study determined that if current conditions continue, the glaciers atop Kilimanjaro will disappear sometime between 2015 and 2020. A March 2005 report indicated that there is almost no remaining glacial ice on the mountain, and it is the first time in 11,000 years that barren ground has been exposed on portions of the summit. Researchers reported Kilimanjaro's glacier retreat was due to a combination of increased sublimation and decreased snow fall.

The Furtwängler Glacier is located near the summit of Kilimanjaro. Between 1976 and 2000, the area of Furtwängler Glacier was cut almost in half, from 113,000 m² (1,220,000 sq ft) to 60,000 m² (650,000 sq ft). During fieldwork conducted early in 2006, scientists discovered a large hole near the center of the glacier. This hole, extending through the

6 m (20 ft) remaining thickness of the glacier to the underlying rock, is expected to grow and split the glacier in two by 2007.

To the north of Kilimanjaro lies Mount Kenya, which at 5,199 m (17,057 ft) is the second tallest mountain on the African continent. Mount Kenya has a number of small glaciers that have lost at least 45% of their mass since the middle of the 20th century. According to research compiled by the U.S. Geological Survey (USGS), there were eighteen glaciers atop Mount Kenya in 1900, and by 1986 only eleven remained. The total area covered by glaciers was 1.6 km² (0.62 sq mi) in 1900, however by the year 2000 only about 25%, or 0.4 km² (0.15 sq mi) remained. To the west of Mounts Kilimanjaro and Kenya, the Ruwenzori Range rises to 5,109 m (16,762 ft). Photographic evidence of this mountain range indicates a marked reduction in glacially covered areas over the past century. In the 35-year period between 1955 and 1990, glaciers on the Ruwenzori Mountains receded about 40%. It is expected that due to their proximity to the heavy moisture of the Congo region, the glaciers in the Ruwenzori Range may recede at a slower rate than those on Kilimanjaro or in Kenya.

South America

A study by glaciologists of two small glaciers in South America reveals another retreat. More than 80% of all glacial ice in the northern Andes is concentrated on the highest peaks in small glaciers of approximately 1 km² (0.39 sq mi) in size. A 1992 to 1998 observation of the Chacaltaya Glacier in Bolivia and Antizana Glacier in Ecuador indicated that between 0.6 m (2.0 ft) and 1.9 m (6.2 ft) of ice was lost per year on each glacier. Figures for Chacaltaya Glacier show a loss of 67% of its volume and 40% of its thickness over the same period. Chacaltaya Glacier has lost 90% of its mass since 1940 and is expected to disappear altogether sometime between 2010 and 2015. Research also indicates that since the mid-1980s, the rate of retreat for both of these glaciers has been increasing. In Colombia, the glaciers atop Nevado del Ruiz have lost more than half their area in the last 40 years. Further south in Peru, the Andes are at a higher altitude overall, and there are approximately 722 glaciers covering an area of 723 km² (279 sq mi). Research in this region of the Andes is less extensive but indicates an overall glacial retreat of 7% between 1977 and 1983. The Quelccaya Ice Cap is the largest tropical icecap in the world, and all of the outlet glaciers from the icecap are retreating. In the case of Qori Kalis Glacier, which is Quelccayas' main outlet glacier, the rate of retreat had reached 155 m (509 ft) per year during the three year period of 1995 to 1998. The melting ice has formed a large lake at the front of the glacier since 1983, and bare ground has been exposed for the first time in thousands of years.

Oceania



Puncak Jaya icecap 1936 USGS



Puncak Jaya glaciers 1972. Left to right: Northwall Firn, Meren Glacier, and Carstensz Glacier.

On the large island of New Guinea, there is photographic evidence of massive glacial retreat since the region was first extensively explored by airplane in the early 1930s. Due to the location of the island within the tropical zone, there is little to no seasonal variation in temperature. The tropical location has a predictably steady level of rain and snowfall, as well as cloud cover year round, and there has been no noticeable change in the amount of moisture which has fallen during the 20th century. The 7 km² (2.7 sq mi) ice cap on Puncak Jaya is the largest on the island, and has retreated from one larger mass into several smaller glacial bodies since 1936. Of these smaller glaciers, research between 1973 and 1976 showed glacier retreat for the Meren Glacier of 200 m (660 ft) while the Carstensz Glacier lost 50 m (160 ft). The Northwall Firn, another large remnant of the icecap that once was atop Puncak Jaya, has itself split into several separate glaciers since 1936. Research presented in 2004 of IKONOS satellite imagery of the New Guinean glaciers provided a dramatic update. The imagery indicated that in the two years from 2000 to 2002, the East Northwall Firn had lost 4.5%, the West Northwall Firn 19.4% and the Carstensz 6.8% of their glacial mass. Researchers also discovered that, sometime between 1994 and 2000, the Meren Glacier disappeared altogether. An expedition to the remaining glaciers on Puncak Jaya in 2010 discovered that the ice on the glaciers there is about 32 metres (105 ft) thick and thinning at a rate of 7 metres (23 ft) annually. At that rate, the remaining glaciers are expected to last another 5 years or 2015. Separate from

the glaciers of Puncak Jaya, another small icecap known to have existed on the summit of Puncak Trikora completely disappeared sometime between 1939 and 1962.

Polar regions

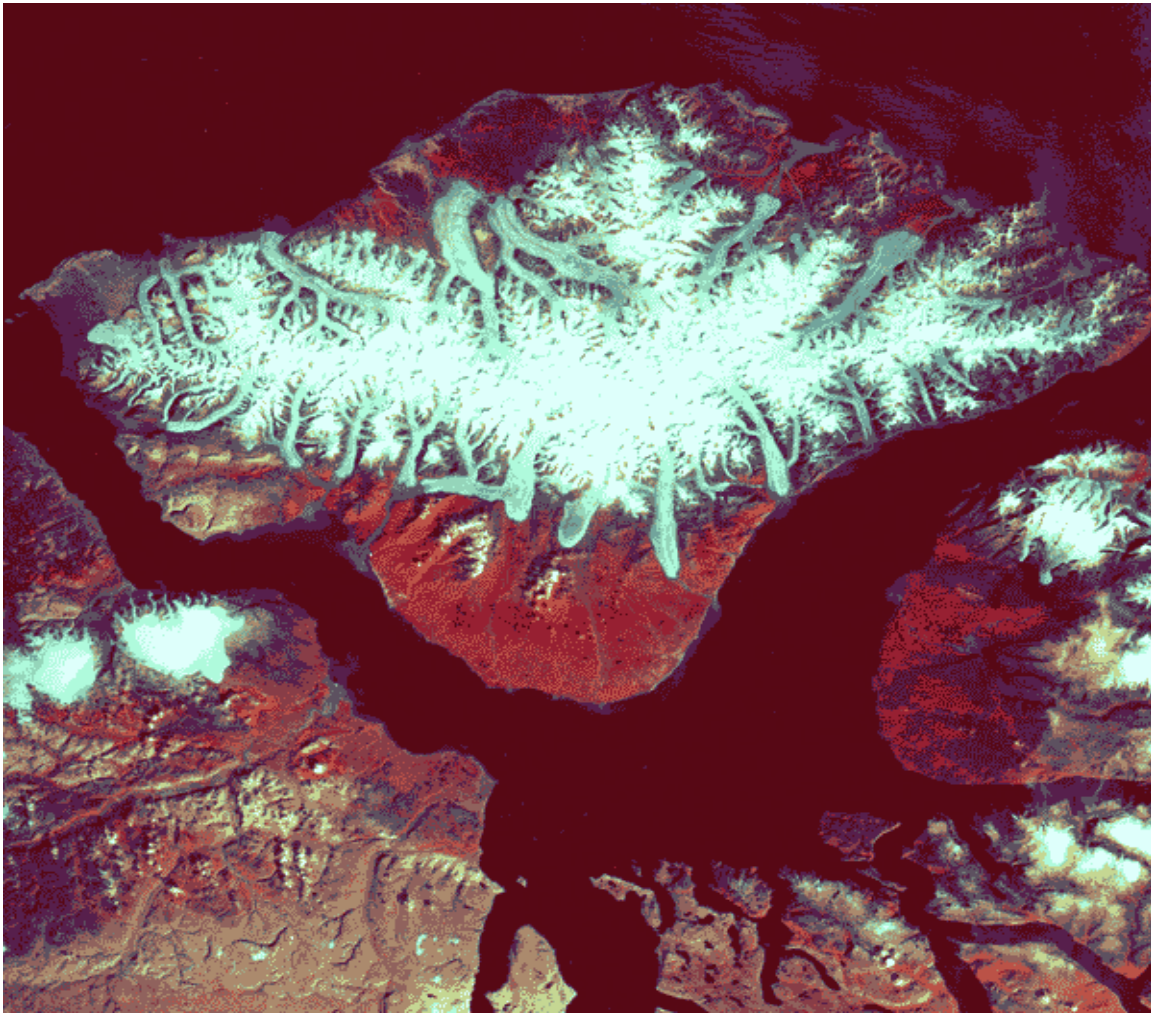
Despite their proximity and importance to human populations, the mountain and valley glaciers of tropical and mid-latitude glaciers amount to only a small fraction of glacial ice on the Earth. About 99% of all freshwater ice is in the great ice sheets of polar and subpolar Antarctica and Greenland. These continuous continental-scale ice sheets, 3 km (1.9 mi) or more in thickness, cap much of the polar and subpolar land masses. Like rivers flowing from an enormous lake, numerous outlet glaciers transport ice from the margins of the ice sheet to the ocean.

Iceland

The northern Atlantic island nation of Iceland is home to the Vatnajökull, which is the largest ice cap in Europe. The Breiðamerkurjökull Glacier is one of the Vatnajökull outlet glaciers, and had receded by as much as 2 km (1.2 mi) between 1973 and 2004. In the early 20th century, Breiðamerkurjökull extended to within 250 m (820 ft) of the ocean, but by 2004 Breiðamerkurjökull's terminus had retreated 3 km (1.9 mi) further inland. This glacier retreat exposed a rapidly expanding lagoon that is filled with icebergs calved from its front. The lagoon is 110 m (360 ft) deep and nearly doubled its size between 1994 and 2004. Mass-balance measurements of Iceland's glaciers show alternating positive and negative mass balance of glaciers during the period 1987–95, but the mass balance has been predominantly negative since. On Hofsjökull ice cap, mass balance has been negative each year from 1995-2005.

Most of the Icelandic glaciers retreated rapidly during the warm decades from 1930 to 1960, slowing down as the climate cooled during the following decade, and started to advance after 1970. The rate of advance peaked in the 1980s, after which it slowed down as a consequence of rapid warming of the climate that has taken place since the mid-1980s. Most glaciers in Iceland began to retreat after 1990, and by 2000 all monitored non-surge type glaciers in Iceland were retreating. An average of 45 non-surgings termini were monitored each year by the Icelandic Glaciological Society from 2000–2005.

Canada



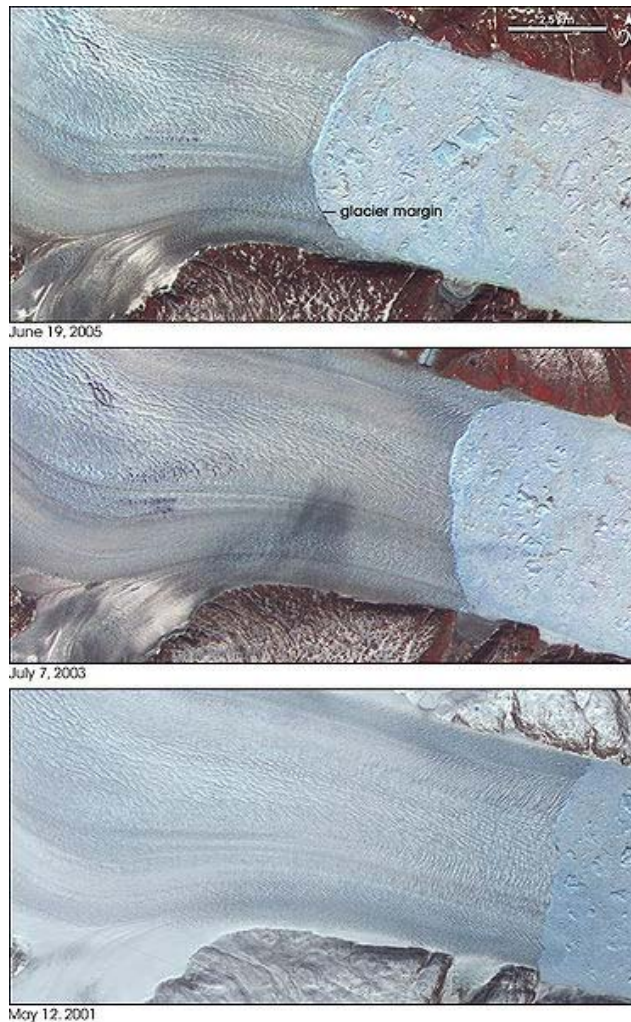
Bylot Ice Cap on Bylot Island, one of the Canadian Arctic islands, August 14, 1975

The Canadian Arctic islands have a number of substantial ice caps, including Penny and Barnes ice caps on Baffin Island, Bylot Ice Cap on Bylot Island, and Devon Ice Cap on Devon Island. All of these ice caps have been thinning and receding slowly. The Barnes and Penny ice caps on Baffin Island have been thinning at over 1 m (3.3 ft) per year in the lower elevations from 1995 to 2000. Overall, between 1995 and 2000, ice caps in the Canadian Arctic lost 25 km² (9.7 sq mi) of ice per year. Between 1960 and 1999, the Devon Ice Cap lost 67 km³ (16 cu mi) of ice, mainly through thinning. All major outlet glaciers along the eastern Devon Ice Cap margin have retreated from 1 km (0.62 mi) to 3 km (1.9 mi) since 1960. On the Hazen Plateau of Ellesmere Island, the Simmon Ice Cap has lost 47% of its area since 1959. If the current climatic conditions continue, the remaining glacial ice on the Hazen Plateau will be gone around 2050. On August 13, 2005 the Ayles Ice Shelf broke free from the north coast of Ellesmere Island, the 66 km² (25 sq mi) ice shelf drifted into the Arctic Ocean. This followed the splitting of the Ward Hunt Ice Shelf in 2002. The Ward Hunt has lost 90% of its area in the last century.

Northern Europe

Arctic islands north of Norway, Finland and Russia have all shown evidence of glacier retreat. In the Svalbard archipelago, the island of Spitsbergen has numerous glaciers. Research indicates that Hansbreen (Hans Glacier) on Spitsbergen retreated 1.4 km (0.87 mi) from 1936 to 1982 and another 400 m (1,300 ft) during the 16-year period from 1982 to 1998. Blomstrandbreen, a glacier in the King's Bay area of Spitsbergen, has retreated approximately 2 km (1.2 mi) in the past 80 years. Since 1960 the average retreat of Blomstrandbreen has been about 35 m (115 ft) a year, and this average was enhanced due to an accelerated rate of retreat since 1995. Similarly, Midre Lovenbreen retreated 200 m (656 ft) between 1977 and 1995. In the Novaya Zemlya archipelago north of Russia, research indicates that in 1952 there was 208 km (129 mi) of glacier ice along the coast. By 1993 this had been reduced by 8% to 198 km (123 mi) of glacier coastline.

Greenland



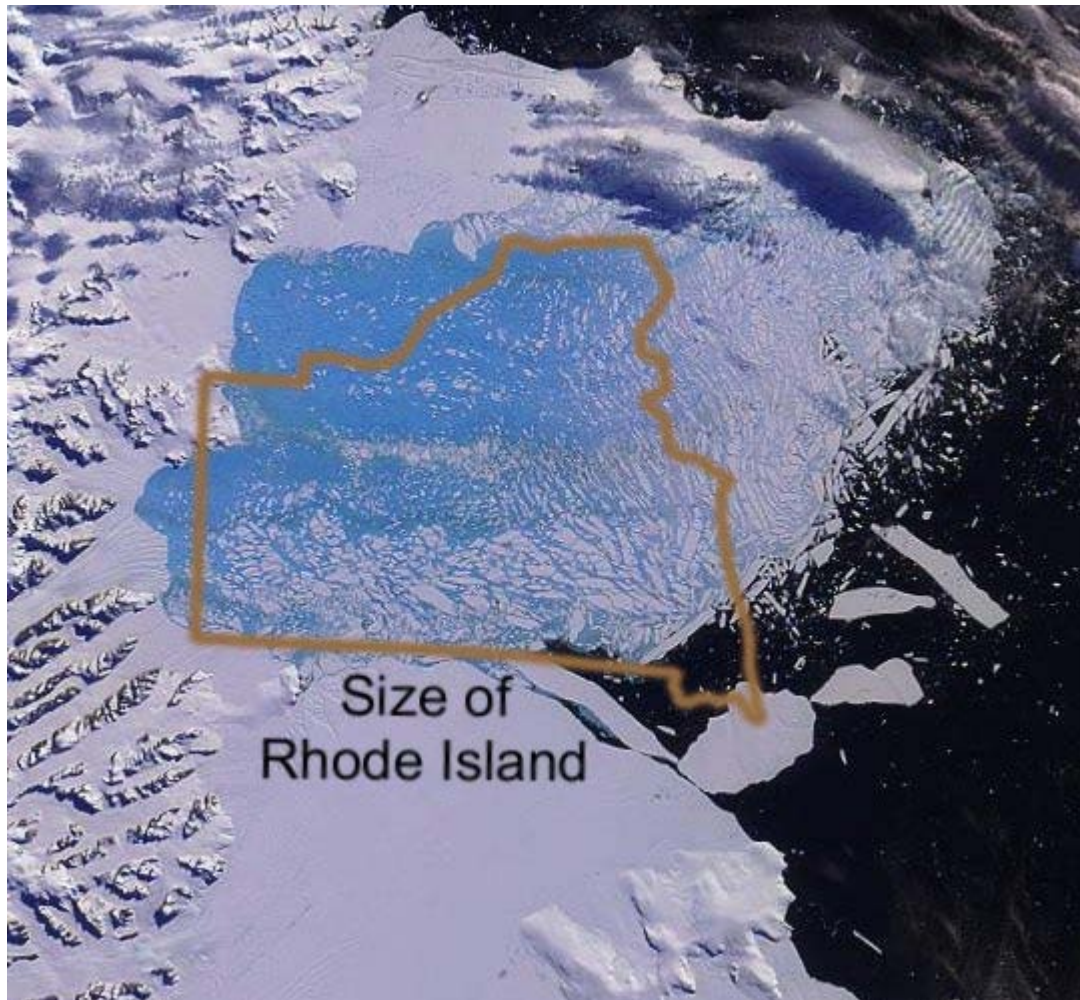
Retreat of the Helheim Glacier, Greenland

In Greenland, glacier retreat has been observed in outlet glaciers, resulting in an increase of the ice flow rate and destabilization of the mass balance of the ice sheet that is their source. The net loss in volume and hence sea level contribution of the Greenland Ice Sheet (GIS) has doubled in recent years from 90 km³ (22 cu mi) to 220 km³ (53 cu mi) per year. Researchers also noted that the acceleration was widespread affecting almost all glaciers south of 70°N by 2005. The period since 2000 has brought retreat to several very large glaciers that had long been stable. Three glaciers that have been researched—Helheim Glacier, Kangerdlugssuaq Glacier, and Jakobshavn Isbræ—jointly drain more than 16% of the Greenland Ice Sheet. In the case of Helheim Glacier, researchers used satellite images to determine the movement and retreat of the glacier. Satellite images and aerial photographs from the 1950s and 1970s show that the front of the glacier had remained in the same place for decades. In 2001 the glacier began retreating rapidly, and by 2005 the glacier had retreated a total of 7.2 km (4.5 mi), accelerating from 20 m (66 ft) per day to 35 m (115 ft) per day during that period.

Jakobshavn Isbræ in west Greenland, a major outlet glacier of the Greenland Ice Sheet, has been the fastest moving glacier in the world over the past half century. It had been moving continuously at speeds of over 24 m (79 ft) per day with a stable terminus since at least 1950. In 2002 the 12 km (7.5 mi) long floating terminus of the glacier entered a phase of rapid retreat, with the ice front breaking up and the floating terminus disintegrating and accelerating to a retreat rate of over 30 m (98 ft) per day. On a shorter timescale, portions of the main trunk of Kangerdlugssuaq Glacier that were flowing at 15 m (49 ft) per day from 1988 to 2001 were measured to be flowing at 40 m (130 ft) per day in the summer of 2005. Not only has Kangerdlugssuaq retreated, it has also thinned by more than 100 m (330 ft).

The rapid thinning, acceleration and retreat of Helheim, Jakobshavn and Kangerdlugssuaq glaciers in Greenland, all in close association with one another, suggests a common triggering mechanism, such as enhanced surface melting due to regional climate warming or a change in forces at the glacier front. The enhanced melting leading to lubrication of the glacier base has been observed to cause a small seasonal velocity increase and the release of meltwater lakes has also led to only small short term accelerations. The significant accelerations noted on the three largest glaciers began at the calving in front and propagated inland and are not seasonal in nature. Thus, the primary source of outlet glacier acceleration widely observed on small and large calving glaciers in Greenland is driven by changes in dynamic forces at the glacier front, not enhanced meltwater lubrication. This was termed the *Jakobshavn Effect* by Terence Hughes at the University of Maine in 1986.

Antarctica



The collapsing Larsen B Ice Shelf in Antarctica is similar in area to the U.S. state of Rhode Island.

The climate of Antarctica is one of intense cold and great aridity. Most of the world's freshwater ice is contained in the great ice sheets that cover the continent of Antarctica. The most dramatic example of glacier retreat on the continent is the loss of large sections of the Larsen Ice Shelf on the Antarctic Peninsula. Ice shelves are not stable when surface melting occurs, and the collapse of Larsen Ice Shelf has been caused by warmer melt season temperatures that have led to surface melting and the formation of shallow ponds of water on the ice shelf. The Larsen Ice Shelf lost 2,500 km² (970 sq mi) of its area from 1995 to 2001. In a 35-day period beginning on January 31, 2002, about 3,250 km² (1,250 sq mi) of shelf area disintegrated. The ice shelf is now 40% the size of its previous minimum stable extent. The recent collapse of Wordie Ice Shelf, Prince Gustav Ice Shelf, Mueller Ice Shelf, Jones Ice Shelf, Larsen-A and Larsen-B Ice Shelf on the Antarctic Peninsula has raised awareness of how dynamic ice shelf systems are. Jones Ice Shelf had an area of 35 km² (14 sq mi) in the 1970s but by 2008 it had disappeared. Wordie Ice Shelf has gone from an area of 1500 square kilometers in 1950 to 140 km² in 2000.

Prince Gustav Ice Shelf has gone from an area of 1600 km² to 11 km² in 2008. After their loss the reduced buttressing of feeder glaciers has allowed the expected speed-up of inland ice masses after shelf ice break-up. The Wilkins Ice Shelf is another ice shelf that has suffered substantial retreat. The ice shelf had an area of 16,000 km² (6,200 sq mi) in 1998 when 1,000 km² (390 sq mi) was lost. In 2007 and 2008 significant rifting developed and led to the loss of another 1,400 km² (540 sq mi) of area. Some of the calving occurred in the Austral winter. The calving seemed to have resulted from preconditioning such as thinning, possibly due to basal melt, as surface melt was not as evident, leading to a reduction in the strength of the pinning point connections. The thinner ice than experienced spreading rifts and breakup. This period culminated in the collapse of an ice bridge connecting the main ice shelf to Charcot Island leading to the loss of an additional 700 km² (270 sq mi) in February–June 2009.

Pine Island Glacier, an Antarctic outflow glacier that flows into the Amundsen Sea, thinned 3.5 m (11 ft)± 0.9 m (3.0 ft) per year and retreated a total of 5 km (3.1 mi) in 3.8 years. The terminus of the Pine Island Glacier is a floating ice shelf, and the point at which it starts to float retreated 1.2 km (0.75 mi) per year from 1992 to 1996. This glacier drains a substantial portion of the West Antarctic Ice Sheet and along with the neighboring Thwaites Glacier, which has also shown evidence of thinning, has been referred to as the weak underbelly of this ice sheet. Additionally, the Dakshin Gangotri Glacier, a small outlet glacier of the Antarctic ice sheet, receded at an average rate of 0.7 m (2.3 ft) per year from 1983 to 2002. On the Antarctic Peninsula, which is the only section of Antarctica that extends well north of the Antarctic Circle, there are hundreds of retreating glaciers. In one study of 244 glaciers on the peninsula, 212 have retreated an average of 600 m (2,000 ft) from where they were when first measured in 1953. The greatest retreat was seen in Sjogren Glacier, which is now 13 km (8.1 mi) further inland than where it was in 1953. There are 32 glaciers that were measured to have advanced; however, these glaciers showed only a modest advance averaging 300 m (980 ft) per glacier, which is significantly smaller than the massive retreat observed.

Impacts of glacier retreat

The continued retreat of glaciers will have a number of different quantitative impacts. In areas that are heavily dependent on water runoff from glaciers that melt during the warmer summer months, a continuation of the current retreat will eventually deplete the glacial ice and substantially reduce or eliminate runoff. A reduction in runoff will affect the ability to irrigate crops and will reduce summer stream flows necessary to keep dams and reservoirs replenished. This situation is particularly acute for irrigation in South America, where numerous artificial lakes are filled almost exclusively by glacial melt. Central Asian countries have also been historically dependent on the seasonal glacier melt water for irrigation and drinking supplies. In Norway, the Alps, and the Pacific Northwest of North America, glacier runoff is important for hydropower.

Some of this retreat has resulted in efforts to slow down the loss of glaciers in the Alps. To retard melting of the glaciers used by certain Austrian ski resorts, portions of the Stubai and Pitztal Glaciers were partially covered with plastic. In Switzerland plastic

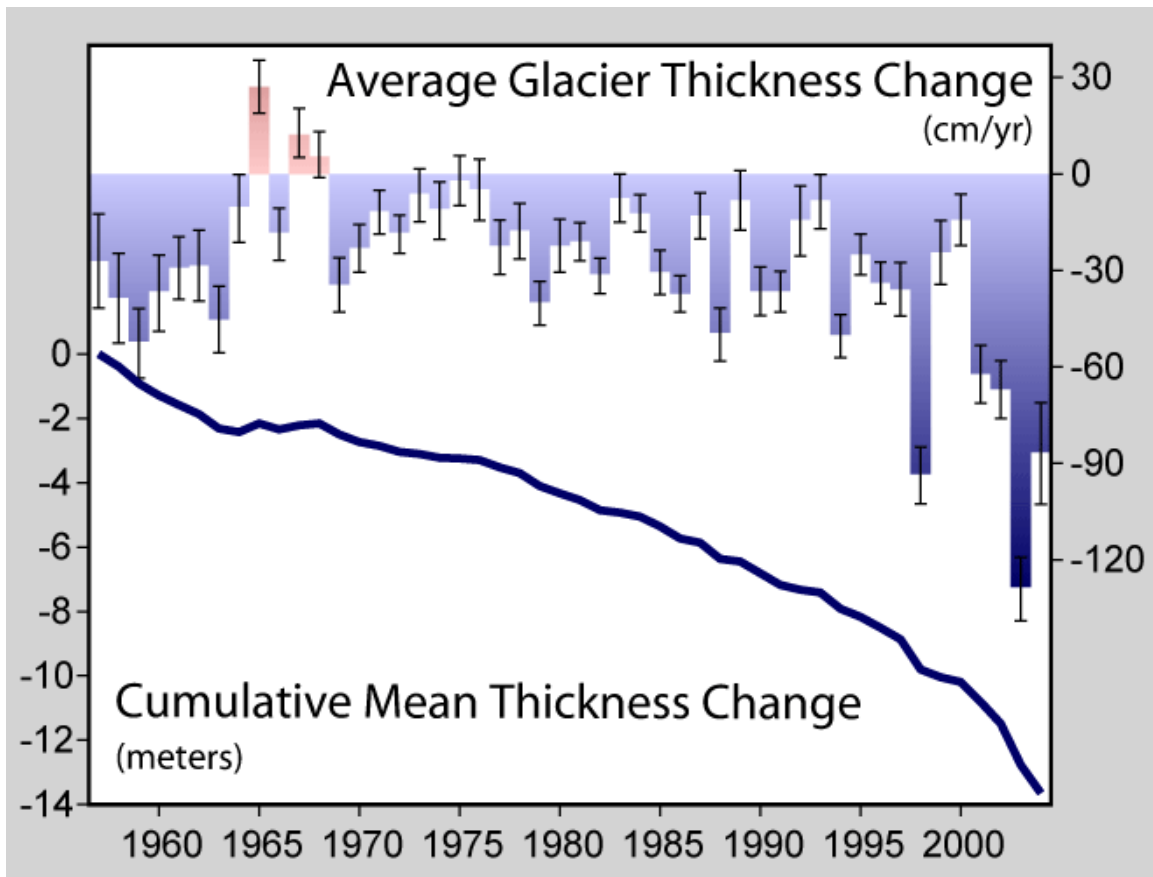
sheeting is also used to reduce the melt of glacial ice used as ski slopes. While covering glaciers with plastic sheeting may prove advantageous to ski resorts on a small scale, this practice is not expected to be economically practical on a much larger scale.

Many species of freshwater and saltwater plants and animals are dependent on glacier-fed waters to ensure the cold water habitat to which they have adapted. Some species of freshwater fish need cold water to survive and to reproduce, and this is especially true with salmon and cutthroat trout. Reduced glacial runoff can lead to insufficient stream flow to allow these species to thrive. Alterations to the ocean currents, due to increased freshwater inputs from glacier melt, and the potential alterations to thermohaline circulation of the world's oceans, may impact existing fisheries upon which humans depend as well.

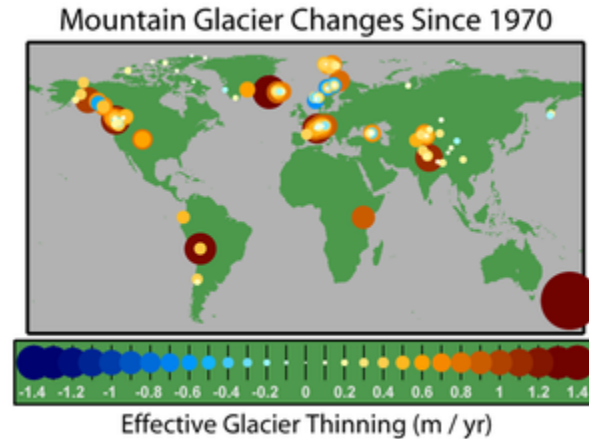
The potential for major sea level rise depends mostly on a significant melting of the polar ice caps of Greenland and Antarctica, as this is where the vast majority of glacial ice is located. If all the ice on the polar ice caps were to melt away, the oceans of the world would rise an estimated 70 m (230 ft). Although previously it was thought that the polar ice caps were not contributing heavily to sea level rise (IPCC 2007), recent studies have confirmed that both Antarctica and Greenland are contributing 0.5 mm a year each to global sea level rise (Cazenave et al. 2009, Velicogna 2009). The fact that the IPCC estimates did not include rapid ice sheet decay into their sea level predictions makes it difficult to ascertain a plausible estimate for sea level rise but recent studies

Chapter- 2

Glacier Mass Balance



Global glacial mass balance in the last fifty years, reported to the WGMS and NSIDC. The downward trend in the late 1980s is symptomatic of the increased rate and number of retreating glaciers.



Map of mountain glacier mass balance changes since 1970. Thinning in yellow and red, thickening in blue. The 1970s were a decade of more positive mass balance than the 1980-2004 period as seen above.

Crucial to the survival of a glacier is its **mass balance**, the difference between accumulation and ablation (melting and sublimation). Climate change may cause variations in both temperature and snowfall, causing changes in mass balance. Changes in mass balance control a glacier's long term behavior and is the most sensitive climate indicator on a glacier. From 1980-2008 the mean cumulative mass loss of glaciers reporting mass balance to the World Glacier Monitoring Service is -12 m. This includes 19 consecutive years of negative mass balances.

A glacier with a sustained negative balance is out of equilibrium and will retreat, while one with a sustained positive balance is out of equilibrium and will advance. Glacier retreat results in the loss of the low elevation region of the glacier. Since higher elevations are cooler than lower ones, the disappearance of the lowest portion of the glacier reduces overall ablation, thereby increasing mass balance and potentially reestablishing equilibrium. However, if the mass balance of a significant portion of the accumulation zone of the glacier is negative, it is in disequilibrium with the local climate. Such a glacier will melt away with a continuation of this local climate. The key symptom of a glacier in disequilibrium is thinning along the entire length of the glacier. For example, Easton Glacier (pictured below) will likely shrink to half its size, but at a slowing rate of reduction, and stabilize at that size, despite the warmer temperature, over a few decades. However, the Grinnell Glacier (pictured below) will shrink at an increasing rate until it disappears. The difference is that the upper section of Easton Glacier remains healthy and snow-covered, while even the upper section of the Grinnell Glacier is bare, melting and has thinned. Small glaciers with shallow slopes such as Grinnell Glacier are most likely to fall into disequilibrium if there is a change in the local climate.

In the case of positive mass balance, the glacier will continue to advance expanding its low elevation area, resulting in more melting. If this still does not create an equilibrium balance the glacier will continue to advance. If a glacier is near a large body of water,

especially an ocean, the glacier may advance until iceberg calving losses bring about equilibrium.

Measurement methods



The Easton Glacier which retreated 255 m from 1990 to 2005 is expected to achieve equilibrium.



Grinnell Glacier in Glacier National Park (U.S.) showing recession since 1850 of 1.1 km
USGS

Mass balance

Mass balance is measured by determining the amount of snow accumulated during winter, and later measuring the amount of snow and ice removed by melting in the summer. The difference between these two parameters is the mass balance. If the amount of snow accumulated during the winter is larger than the amount of melted snow and ice during the summer, the mass balance is positive and the glacier has increased in volume. On the other hand, if the melting of snow and ice during the summer is larger than the supply of snow in the winter, the mass balance is negative and the glacier volume decreases. Mass balance is reported in meters of water equivalent. This represents the average thickness gained (positive balance) or lost (negative balance) from the glacier during that particular year.

To determine mass balance in the accumulation zone, snowpack depth is measured using probing, snowpits or crevasse stratigraphy. Crevasse stratigraphy makes use of annual

layers revealed on the wall of a crevasse. Akin to tree rings, these layers are due to summer dust deposition and other seasonal effects. The advantage of crevasse stratigraphy is that it provides a two-dimensional measurement of the snowpack layer, not a point measurement. It is also usable in depths where probing or snowpits are not feasible. In temperate glaciers, the insertion resistance of a probe increases abruptly when its tip reaches ice that was formed the previous year. The probe depth is a measure of the net accumulation above that layer. Snowpits dug through the past winter's residual snowpack are used to determine the snowpack depth and density. The snowpack's mass balance is the product of density and depth. Regardless of depth measurement technique the observed depth is multiplied by the snowpack density to determine the accumulation in water equivalent. It is necessary to measure the density in the spring as snowpack density varies. Measurement of snowpack density completed at the end of the ablation season yield consistent values for a particular area on temperate alpine glaciers and need not be measured every year. In the ablation zone, ablation measurements are made using stakes inserted vertically into the glacier either at the end of the previous melt season or the beginning of the current one. The length of stake exposed by melting ice is measured at the end of the melt (ablation) season. Most stakes must be replaced each year or even mid-way through the summer.



Measuring snowpack in a crevasse on the Easton Glacier, North Cascades, USA, the two dimensional nature of the annual layers is apparent



Measuring snowpack on the Taku Glacier in Alaska, this is a slow and inefficient process, but is very accurate

Net balance

Net balance is the mass balance determined between successive mass balance minimums. This is the stratigraphic method focusing on the minima representing a stratigraphic horizon. In the northern mid-latitudes, a glacier's year follows the hydrologic year, starting and ending near the beginning of October. The mass balance minimum is the end of the melt season. The net balance is then the sum of the observed winter balance (bw) normally measured in April or May and summer balance (bs) measured in September or early October.



Measuring snowpack on the Easton Glacier by probing to the previous impenetrable surface, this provides a quick accurate point measurement of snowpack

Annual balance

Annual balance is the mass balance measured between specific dates. The mass balance is measured on the fixed date each year, again sometime near the start of October in the mid northern latitudes.

Geodetic methods

Geodetic methods are an indirect method for the determination of mass balance of glacier. Maps of a glacier made at two different points in time can be compared and the difference in glacier thickness observed used to determine the mass balance over a span of years. This is best accomplished today using Differential Global Positioning System. Sometimes the earliest data for the glacier surface profiles is from images that are used to make topographical maps and digital elevation models. Aerial mapping or photogrammetry is now used to cover larger glaciers and icecaps such found in Antarctica and Greenland, however, because of the problems of establishing accurate ground control points in mountainous terrain, and correlating features in snow and where shading is common, elevation errors are typically not less than 10 m (32 ft). Laser altimetry provides a measurement of the elevation of a glacier along a specific path, e.g., the glacier centerline. The difference of two such measurements is the change in thickness, which provides mass balance over the time interval between the measurements. Again a good method over a span of time but not for annual change detection. The value of geodetic programs is providing an independent check of traditional mass balance work, by comparing the cumulative changes over ten or more years.

Mass balance research worldwide

Mass balance studies have been carried out in various countries worldwide, but have mostly been conducted in the Northern Hemisphere due to there being more mid-latitude glaciers in that hemisphere. The World Glacier Monitoring Service annually compiles the mass balance measurements from around the world. From 2002-2006, continuous data is available for only 7 glaciers in the southern hemisphere and 76 glaciers in the Northern Hemisphere. The mean balance of these glaciers was its most negative in any year for 2005/06. The similarity of response of glaciers in western North America indicates the large scale nature of the driving climate change.

Alaska

The Taku Glacier near Juneau, Alaska has been studied by the Juneau Icefield Research Program since 1946, and is the longest continuous mass balance study of any glacier in North America. Taku is the world's thickest known temperate alpine glacier, and experienced positive mass balance between the years 1946 and 1988, resulting in a huge advance. The glacier has since been in a negative mass balance state, which may result in a retreat if the current trends continue. The Juneau Icefield Research Program also has studied the mass balance of the Lemon Creek Glacier since 1953. The glacier has had an average annual balance of -0.44 m per year from 1953–2006, resulting in a mean loss of over 27 m of ice thickness. This loss has been confirmed by laser altimetry.

Austrian Glacier Mass Balance

The mass balance of Hintereisferner and Kesselwandferner glaciers in Austria have been continuously monitored since 1952 and 1965 respectively. Having been continuously measured for 55 years, Hintereisferner has one of the longest periods of continuous study of any glacier in the world, based on measured data and a consistent method of evaluation. Currently this measurement network comprises about 10 snow pits and about 50 ablation stakes distributed across the glacier. In terms of the cumulative specific balances, Hintereisferner experienced a net loss of mass between 1952 and 1964, followed by a period of recovery till 1968. Hintereisferner reached an intermittent minimum in 1976, briefly recovered in 1977 and 1978 and has continuously lost mass in the 30 years since then. Total mass loss has been 26 m since 1952. Sonnblickkees Glacier has been measured since 1957 and the glacier has lost 12 m of mass, an average annual loss of -0.23 m per year.

New Zealand

Glacier mass balance studies have been ongoing in New Zealand glaciers since 1957. Tasman Glacier has been studied since then by the New Zealand Geological Survey and later by the Ministry of Works, measuring the ice stratigraphy and overall movement. However, even earlier fluctuation patterns were documented on Franz Josef and Fox Glaciers in 1950. Other glaciers on the South Island studied include Ivory Glacier since 1968, while on the North Island, glacier retreat and mass balance research has been

conducted on the glaciers on Mount Ruapehu since 1955. On Mount Ruapehu, permanent photographic stations allow repeat photography to be used to provide photographic evidence of changes to the glaciers on the mountain over time.

North Cascade glacier mass balance program

The North Cascade Glacier Climate Project measures the annual balance of 10 glaciers, more than any other program in North America. These records extend from 1984–2008 and represent the only set of records documenting the mass balance changes of an entire glacier clad range. To monitor an entire glaciated mountain range in North America, which was listed as a high priority of the National Academy of Sciences in 1983. North Cascade glaciers annual balance has averaged -0.48 m/a from 1984–2008, a cumulative thickness loss of over 13 m or 20–40% of their total volume since 1984 due to negative mass balances. The trend in mass balance is becoming more negative which is fueling more glacier retreat and thinning.

Norway mass balance program

Norway maintains the most extensive mass balance program in the world and is largely funded by the hydropower industry. Mass balance measurements are currently performed on twelve glaciers in Norway. In southern Norway six of the glaciers have been measured for 42 consecutive years or more, and they constitute a west-east profile reaching from the very maritime Ålfotbreen Glacier, close to the western coast, to the very continental Gråsubreen Glacier, in the eastern part of Jotunheimen. Storbreen Glacier in Jotunheimen has been measured for a longer period of time than any other glacier in Norway, a total of over 55 years, while Engabreen Glacier has the longest series (35 years) in northern Norway. The Norwegian program is where the traditional methods of mass balance measurement were largely derived.

Sweden Storglaciären

The Tarfala Research Station in the Kebnekaise region of northern Sweden is operated by Stockholm University. It was here that the first mass balance program was initiated immediately after World War II, and continues to the present day. This survey was the initiation of the mass balance record of Storglaciären Glacier, and constitutes the longest continuous study of this type in the world. Storglaciären has had a cumulative negative mass balance from 1946-2006 of -17 m. The program began monitoring the Rabots Glaciär in 1982, Riukojietna in 1985, and Mårmaglaciären in 1988. All three of these glaciers have had a strong negative mass balance since initiation.

Iceland Glacier mass balance

Glacier mass balance is measured once or twice annually on numerous stakes on the several ice caps in Iceland by the National Energy Authority. Regular pit and stake mass-balance measurements have been carried out on the northern side of Hofsjökull since 1988 and likewise on the Þrándarjökull since 1991. Profiles of mass balance (pit and

stake) have been established on the eastern and south-western side of Hofsjökull since 1989. Similar profiles have been assessed on the Tungnaárjökull, Dyngjujökull, Köldukvíslarjökull and Brúarjökull outlet glaciers of Vatnajökull since 1992 and the Eyjabakkajökull outlet glacier since 1991.

Swiss mass balance program

Temporal changes in the spatial distribution of the mass balance result primarily from changes in accumulation and melt along the surface. As a consequence, variations in the mass of glaciers reflect changes in climate and the energy fluxes at the Earth's surface. The Swiss glaciers Gries in the central Alps and Silvretta in the eastern Alps, have been measured for many years. The distribution of seasonal accumulation and ablation rates are measured in-situ. Traditional field methods are combined with remote sensing techniques to track changes in mass, geometry and the flow behaviour of the two glaciers. These investigations contribute to the Swiss Glacier Monitoring Network and the International network of the World Glacier Monitoring Service (WGMS).

United States Geological Survey (USGS)

The USGS operates a long-term "benchmark" glacier monitoring program which is used to examine climate change, glacier mass balance, glacier motion, and stream runoff. This program has been ongoing since 1965 and has been examining three glaciers in particular. Gulkana Glacier in the Alaska Range and Wolverine Glacier in the Coast Ranges of Alaska have both been monitored since 1965, while the South Cascade Glacier in Washington State has been continuously monitored since the International Geophysical Year of 1957. This program monitors one glacier in each of these mountain ranges, collecting detailed data to understand glacier hydrology and glacier climate interactions.

Geological Survey of Canada-Glaciology Section (GSC)

The GSC operates Canada's Glacier-Climate Observing System as part of its Climate Change Geoscience Program. With its University partners, it conducts monitoring and research on glacier-climate changes, water resources and sea level change using a network of reference observing sites located in the Cordillera and the Canadian Arctic Archipelago. This network is augmented with remote sensing assessments of regional glacier changes. Sites in the Cordillera include the Helm, Place, Andrei, Kaskakwulsh, Haig, Peyto, Ram River, Castle Creek, Kwadacha and Bologna Creek Glaciers; in the Arctic Archipelago include the White, Baby and Grise Glaciers and the Devon, Meighen, Melville and Agassiz Ice Caps. GSC reference sites are monitored using the standard stake based glaciological method (stratigraphic) and periodic geodetic assessments using airborne lidar. Detailed information, contact information and database available here: Helm Glacier (-33 m) and Place Glacier (-27 m) have lost more than 20% of their entire volume, since 1980, Peyto Glacier (-20 m) is close to this amount. The Canadian Arctic White Glacier has not been as negative at (-6 m) since 1980.

Bolivia mass balance network

The glacier monitoring network in Bolivia, a branch of the glacio-hydrological system of observation installed throughout the tropical Andes mountains by IRD and partners since 1991, has monitored mass balance on Zongo (6000 m asl), Chacaltaya (5400 m asl) and Charquini glaciers (5380 m asl). A system of stakes has been used, with frequent field observations, as often as monthly. These measurements have been made in concert with energy balance to identify the cause of the rapid retreat and mass balance loss of these tropical glaciers.

Chapter- 3

Glacial Lake Outburst Flood



Hubbard Glacier, Alaska squeezes towards Gibert Point on 20 May 2002. The glacier is close to sealing off Russell Fjord (top) from Disenchantment Bay (below).

A **glacial lake outburst flood (GLOF)** can occur when a lake contained by a glacier (called Jökulhlaup if it was a subglacial lake, marginal lake drainage if it was dammed between ice and the ground) or a terminal moraine dam fails. This can happen due to erosion, a buildup of water pressure, an avalanche of rock or heavy snow, an earthquake or cryoseism, volcanic eruptions under the ice, or if a large enough portion of a glacier breaks off and massively displaces the waters in a glacial lake at its base.

Definition



In this Hubbard Glacier image from 16 July 2002, the glacier has closed off Russell Fjord from Disenchantment Bay. The waters behind the glacier rose 61 feet (19 m) in 10 weeks, creating a short lived Russell Lake.

A glacial lake outburst flood is created when water dammed by a glacier or a moraine is released. A water body that is dammed by the front of a glacier is called a marginal lake, and a water body that is capped by the glacier is called a sub-glacial lake. When the former bursts it may also be called a marginal lake drainage, and when the latter bursts it may be called a jökulhlaup.

A jökulhlaup is thus a sub-glacial outburst flood. Jökulhlaup is an Icelandic term that has been adapted into the English language, and originally only referred to glacial outburst

floods from Vatnajökull, which are triggered by volcanic eruptions, but now is accepted to describe any abrupt and large release of sub-glacial water.

Glacial lakes come in various sizes, but may hold millions to hundreds of millions of cubic meters of water. Catastrophic failure of the containing ice or glacial sediment can release this water over a timespan of minutes to days. Peak flows as high as 15,000 cubic meters per second have been recorded in these events, suggesting that the v-shaped canyon of a normally small mountain stream could suddenly develop an extremely turbulent and fast-moving torrent some 50 metres (160 ft) deep. On a downstream floodplain, it suggests a somewhat slower inundation spreading as much as 10 kilometres (6.2 mi) wide. Both scenarios are horrific threats to lives, property and infrastructure.

Monitoring



The Hubbard Glacier is overwhelmed on 14 August 2002 in the second largest GLOF in historical times.

The United Nations has a series of monitoring efforts to help prevent death and destruction in regions that are likely to experience these events. The importance of this situation has magnified over the past century due to increased populations, and the increasing number of glacial lakes that have developed due to glacier retreat. While all countries with glaciers are susceptible to this problem, central Asia, the Andes regions of

South America and those countries in Europe that have glaciers in the Alps, have been identified as the regions at greatest risk.

There are a number of imminent deadly GLOFs situations that have been identified worldwide. The Tsho Rolpa glacier lake is located in the Rolwaling Valley, about 110 kilometres (68 mi) northeast of Kathmandu, Nepal, at an altitude of 4,580 metres (15,030 ft). The lake is dammed by a 150 metres (490 ft) high unconsolidated terminal moraine dam. The lake is growing larger every year due to the melting and retreat of the Trakarding Glacier, and has become the largest and most dangerous glacier lake in Nepal, with approximately 90 to 100 million m³ (117 to 130 million yd³) of water stored.

Examples

Iceland



Remains of a steel bridge in Skaftafell National Park after a glacial outburst

The most famous are the immense *jökulhlaup* released from the Vatnajökull Ice Cap in Iceland. It is not by chance that the term *jökulhlaup* comes from Icelandic, as the south of Iceland has very often been the victim of such catastrophes. This was the case in 1996, when the volcano under the Grímsvötn lakes belonging to the Vatnajökull glacier erupted, and the river Skeiðará flooded the land in front of Skaftafell National Park. The

jökulhlaup reached a flow rate of 50,000 cubic meters per second, and destroyed parts of the Hringvegur (Ring Road or Iceland Road #1). The flood carried ice floes that weighed up to 5000 tons with icebergs between 100-200 tons striking the Gigjukvisl Bridge of the Ring Road (the ruins are well marked with explanatory signs today as a popular tourist stop). The tsunami released was up to 4 metres (13 ft) high and 600 metres (660 yd) wide. The flood carried with it 185 million tons of silt. The jökulhlaup flow made it for several days the 2nd largest river (in terms of water flow) after the Amazon.

After the flooding, some icebergs 10 metres (33 ft) high could be seen on the banks of the river where the glacier run had left them behind. The peak water release from a lake that develops around the Grímsvötn Volcanic Crater in the center of the Vatnajökull ice cap generates flows that exceed the volume of the Mississippi River. The outbursts have occurred in 1954, 1960, 1965, 1972, 1976, 1982, 1983, 1986, 1991 and 1996. In 1996, the eruption melted 3 cubic kilometres (0.72 cu mi) of ice and yielded an outburst of 6,000 cubic metres (7,800 cu yd) per second at peak flow.

Alaska

Some jökulhlaups release annually. Lake George near the Knik River had large annual outbreaks from 1918 to 1966. Since 1966 the Knik Glacier has retreated and an ice-dam is no longer created. Lake George might resume annual floods if the glacier thickens again and blocks the valley (Post and Mayo, 1971). Almost every year, GLOFs occur in two locations in southeastern Alaska, one of which is Abyss Lake. The releases associated with the Tulsequah Glacier near Juneau often inundate a nearby airstrip. About 40 cabins could potentially be affected and a few have been damaged by the larger floods. Events from Salmon Glacier near Hyder have damaged roads near the Salmon River.

Contiguous United States

Immense prehistoric GLOFs, known as the Missoula Floods, occurred in North American's Columbia River watershed towards the end of the last ice age. They were the result of periodic breaches of ice dams in present day Montana, resulting in the draining of a body of water now known as Glacial Lake Missoula.

Glacial River Warren drained Glacial Lake Agassiz during the Wisconsinian glaciation, in whose bed the now mild Minnesota River flows. This river seasonably drained glacial meltwater into what is now the Upper Mississippi River. The region now termed the Driftless Area of North America was contemporaneously also subject to glacial outburst floods from Glacial Lake Grantsburg, and Glacial Lake Duluth during all three phase of the last ice age.

Between 6 and 10 September 2003, a GLOF occurred from Grasshopper Glacier in the Wind River Mountains, Wyoming. A proglacial lake at the head of the glacier burst through a glacial dam, and water from the lake carved a trench down the center of the glacier for more than 0.8 kilometres (0.5 mi). An estimated 2,460,000 cubic metres

(650,000,000 US gal) gallons of water were released in four days, raising the flow level of Dinwoody Creek from 5.66 cubic metres (200 cu ft) per second to 25.4 cubic metres (900 cu ft) per second, as recorded at a gauging station 27 kilometres (17 mi) downstream. Debris from the flood was deposited more than 32 kilometres (20 mi) along the creek. The GLOF has been attributed to the rapid retreat of the glacier, which has been ongoing since the glacier was first accurately measured in the 1960s.

Canada

In 1978 debris flows triggered by a jökulhlaup from Cathedral Glacier destroyed part of the Canadian Pacific railway track, derailed a freight train and buried parts of the Trans Canada Highway

In 1994 a jökulhlaup occurred at Farrow Creek, British Columbia.

In 2003 a jökulhlaup drained into Lake Tuborg on Ellesmere Island, and the events and its aftermath were monitored. The ice-dammed lake drained catastrophically by floating its ice dam. This is an extremely rare occurrence in the Canadian High Arctic, where most glaciers are cold based, and ice-dammed lakes typically drain slowly by overtopping their dams.

It has been suggested that Heinrich events during last glaciation could have been caused by gigantic jökulhlaups from a Hudson Bay lake dammed by ice at the mouth of Hudson Strait.

Bhutan

GLOFs occur with regularity in the valleys and low lying river plains of Bhutan. In the recent past, flash floods have occurred in the Thimphu, Paro and Punankha-Wangdue valleys. Of the 2674 glacial lakes in Bhutan, 24 have been identified by a recent study as candidates for GLOFs in the near future. In October 1994, a GLOF 90 kilometres (56 mi) upstream from Punakha Dzong caused massive flooding on the Pho Chhu River, damaging the dzong and causing casualties.

England/France

The Strait of Dover is thought to have been created around 200,000 years ago by a catastrophic GLOF caused by the breaching of the Weald-Artois Anticline, which acted as a natural dam that held back a large lake in the Doggerland region, now submerged under the North Sea. The flood would have lasted several months, releasing as much as one million cubic metres of water per second. The cause of the breach is not known but may have been caused by an earthquake or simply the build-up of water pressure in the lake. As well as destroying the isthmus that connected Britain to continental Europe, the flood carved a large bedrock-floored valley down the length of the English Channel, leaving behind streamlined islands and longitudinal erosional grooves characteristic of catastrophic megaflood events.

Nepal

Even though GLOF events have been occurring in Nepal for many decades, the Dig Tsho glacier outburst, which took place in 1985, has triggered detailed study of this phenomenon. In 1996, the Water and Energy Commission Secretariat (WECS) of Nepal reported that five lakes were potentially dangerous, namely, Dig Tsho, Imja, Lower Barun, Tsho Rolpa, and Thulagi, all lying above 4100 m. A recent study done by ICIMOD and UNEP (UNEP, 2001) reported 27 potentially dangerous lakes in Nepal. In ten of them GLOF events have occurred in the past few years and some have been regenerating after the event. Additional dangerous glacial lakes may exist in parts of Tibet that are drained by streams crossing into Nepal, raising the possibility of outburst incidents in Tibet causing downstream damage in Nepal. The Gandaki River basin is reported to contain 1025 glaciers and 338 lakes.

Thulagi glacier The Thulagi glacier, which is located in the Upper Marsyangdi River basin, is one out of the two moraine-dammed lakes (supra-glacial lakes), identified as a potentially dangerous lake. The KfW, Frankfurt, the BGR (Federal Institute for Geosciences and Natural Resources, Germany), in cooperation with the Department of Hydrology and Meteorology in Kathmandu, have carried out studies on the Thulagi Glacier and have concluded that even assuming the worst case, a disastrous outburst of the lake can be excluded in the near future.

Pakistan

In 1929 a GLOF from the Chong Khumdan Glacier in the Karakoram caused flooding on the Indus River 1,200 km downstream (a maximum flood rise of 8.1 m at Attock).

China

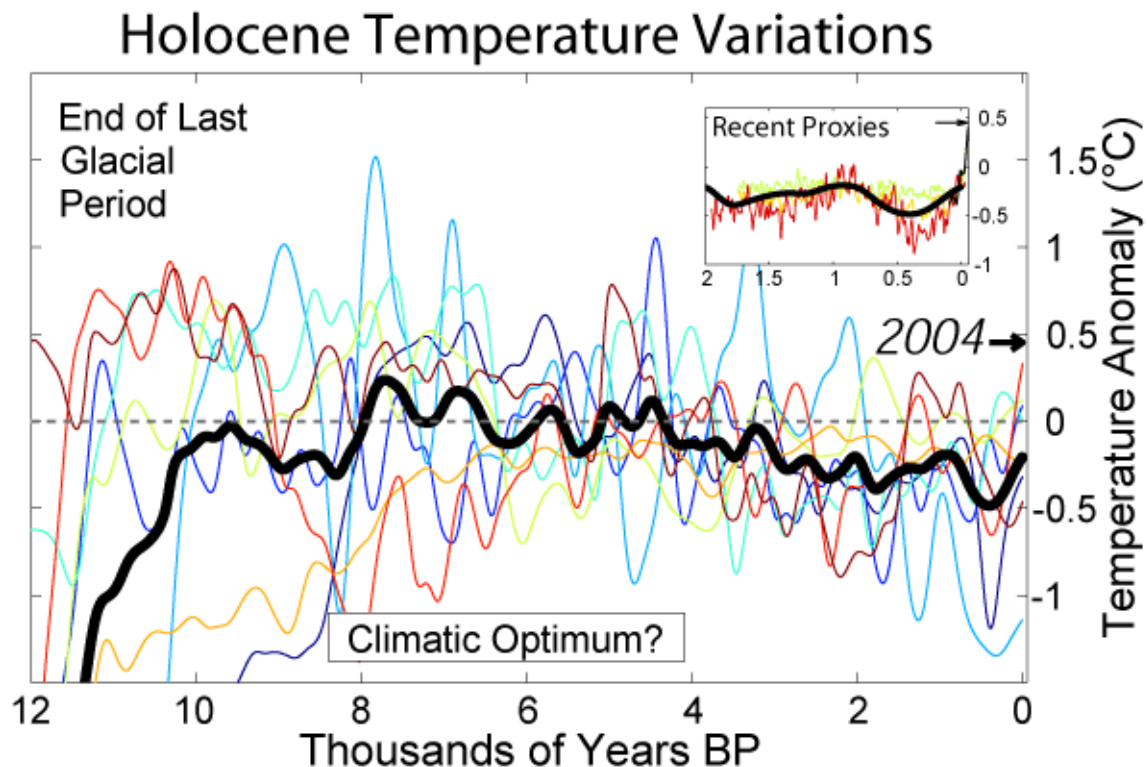
Longbasaba and Pida lakes are two moraine-dammed lakes at an altitude of about 5700 m in the Chinese Himalayas. Due to the rise of temperature, the areas of the Longbasaba and Kaer glaciers decreased by 8.7% and 16.6% from 1978 to 2005. Water from glaciers directly flowed into Longbasaba and Pida lakes, and the area of the two lakes increased by 140% and 194%. According to the report of the Hydrological Department of the Tibet Autonomous Region (HDTAR) in 2006, if a GLOF had occurred at the two lakes, 23 towns and villages, where more than 12,500 people live, would have been endangered.

In Tibet, one of the major barley producing areas of the Tibetan Plateau was destroyed by GLOFs in August 2000. More than 10,000 homes, 98 bridges and dykes were destroyed and its estimated cost was about \$75 million. The farming communities faced food shortages that year by losing their grain and livestock.

A major GLOF was reported in 1978 in the valley of the Shaksgam River in the Chinese Karakoram.

Chapter- 4

Holocene Glacial Retreat

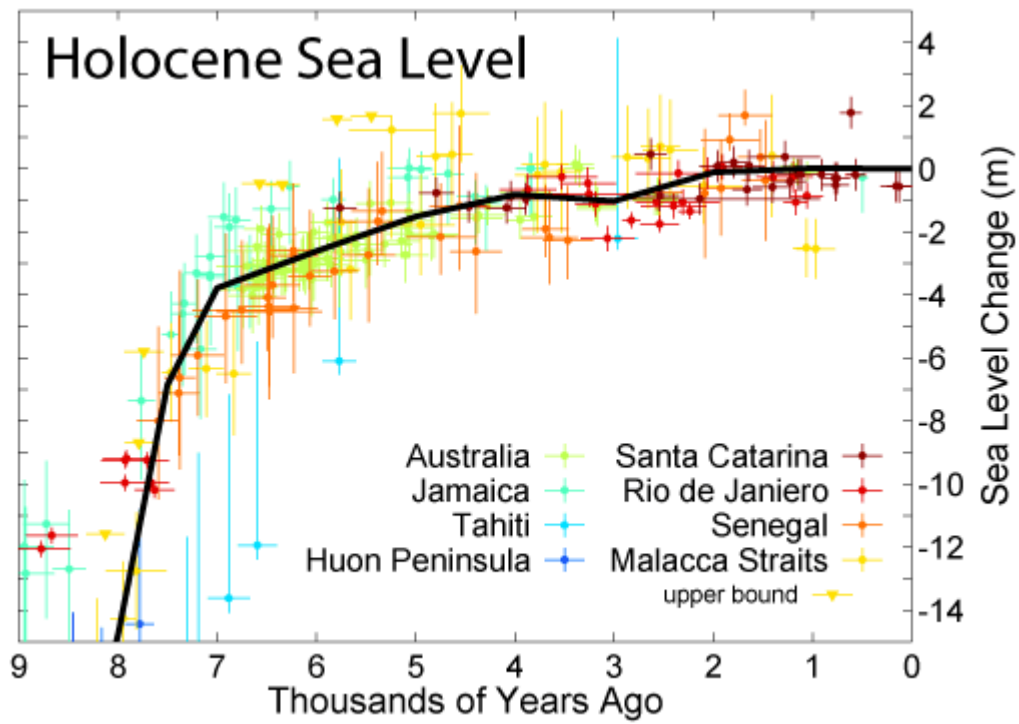


Eight records of local temperature variability on multi-centennial scales throughout the course of the Holocene, and an average of these (thick dark line).

Holocene glacial retreat had a profound effect on landscapes in many areas that were covered by ice at the Last Glacial Maximum. The many valleys of the Cairngorms, a mountainous region in the Eastern Scottish Highlands are littered with deposits from this period.

Geographical alterations

Evidences of the retreat of the ice sheets



Changes in sea level during the Holocene

- Terminal moraine



The *Salpausselkä* terminal moraines in Southern Finland



The Marseilles terminal moraine located southwest of Chicago



Alpine terminal moraine near St. Moritz, Upper Engadin, Switzerland, view east towards the Muretto pass, the national border with Italy

A **terminal moraine**, also called **end moraine**, is a moraine that forms at the end of the glacier called the snout.

Terminal moraines mark the maximum advance of the glacier. An end moraine is at the present boundary of the glacier.

Terminal moraines are one of the most prominent types of moraines in the Arctic. One famous terminal moraine is the Giant's Wall in Norway which, according to legend, was built by giants to keep intruders out of their realm. It is now known that terminal moraines are created at the edge of the greatest extent of the glacier. At this point, the debris that has been accumulated by plucking and abrasion, that has been pushed by the front edge of the ice is driven no farther, but instead is dumped in a heap. Because the glacier acts very much like a conveyor belt, the longer it stays in one place, the greater the amount of material that will be deposited. The moraine is left as the marking point of the terminal extent of the ice.

In North America, the Outer Lands is a name given to the terminal moraine archipelago of the northeast United States (Cape Cod, Martha's Vineyard, Nantucket, Block Island and Long Island). Other prominent examples of terminal moraines are the Tinley

Moraine and the Valparaiso Moraine, perhaps the best examples of terminal moraines in North America. These moraines are most clearly seen southwest of Chicago.

In Europe, virtually all the terrain in the central Netherlands is made up of an extended terminal moraine. In Switzerland, alpine terminal moraines can be found, one striking example being the moraine at the end of the valley of the glacier Forno in the south-eastern canton of Graubünden near St. Moritz and the Italian border.

The modern Ohio River was formed when the river was temporarily dammed just southwest of Louisville, Kentucky, creating a large lake until the dam burst. The Ohio River largely supplanted the former Teays River drainage system, which was disrupted by the glaciers.

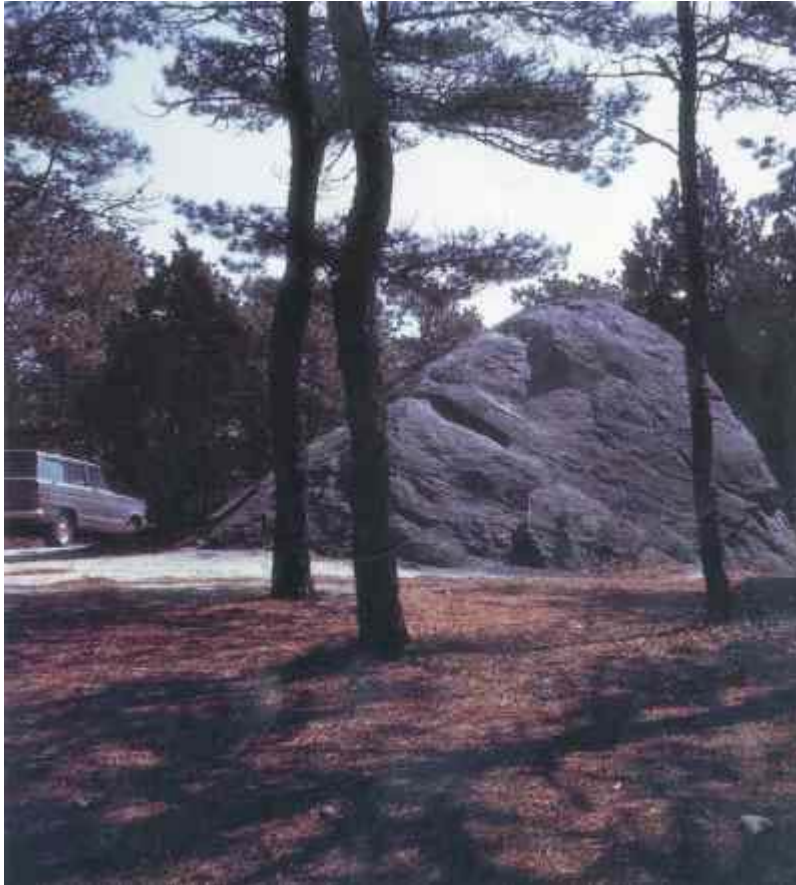
- Ancient shores

Ancient Lake Chicago, on the southern margin of the Wisconsin Glacier, found successive lower outlets as the glacier retreated, until the Saint Lawrence River route was uncovered. Corresponding to each level, remnant lake shore features may be found in many areas. One prehistoric shoreline is delineated by Bluff Avenue, a north-south street on the La Grange, Illinois east side.

- Glacial erratics



The Giebichenstein in Stöckse, Germany



Doane Rock, at Cape Cod National Seashore

A **glacial erratic** is a piece of rock that differs from the size and type of rock native to the area in which it rests. "Erratics" take their name from the Latin word *errare*, and are carried by glacial ice, often over distances of hundreds of kilometres. Erratics can range in size from pebbles to large boulders such as Big Rock (16,500 tons) in Alberta.

Geologists identify erratics by studying the rocks surrounding the position of the erratic and the composition of the erratic itself. Erratics are significant because:

- Since they are transported by glaciers, they are one of a series of indicators which mark the path of prehistoric glacier movement. Their lithographic origin can be traced to the parent bedrock, allowing for confirmation of the ice flow route.
- They can be transported by ice-rafting. This allows quantification of the extent of glacial flooding resulting from ice dam failure which release the waters stored in proglacial lakes such as Lake Missoula. Erratics released by ice-rafts that were stranded and subsequently melt, dropping their load, allow characterization of the high water marks for transient floods in areas like temporary Lake Lewis.
- Erratics dropped by icebergs melting in the ocean can be used to track Antarctic and Arctic-region glacial movements for periods prior to record retention. These

can be correlated with ocean temperatures and levels to better understand and calibrate models of the global climate.

Formation of erratics



Multiple erratics on the terminal moraine of the Okanagon Lobe. Cascade mountains in the background.

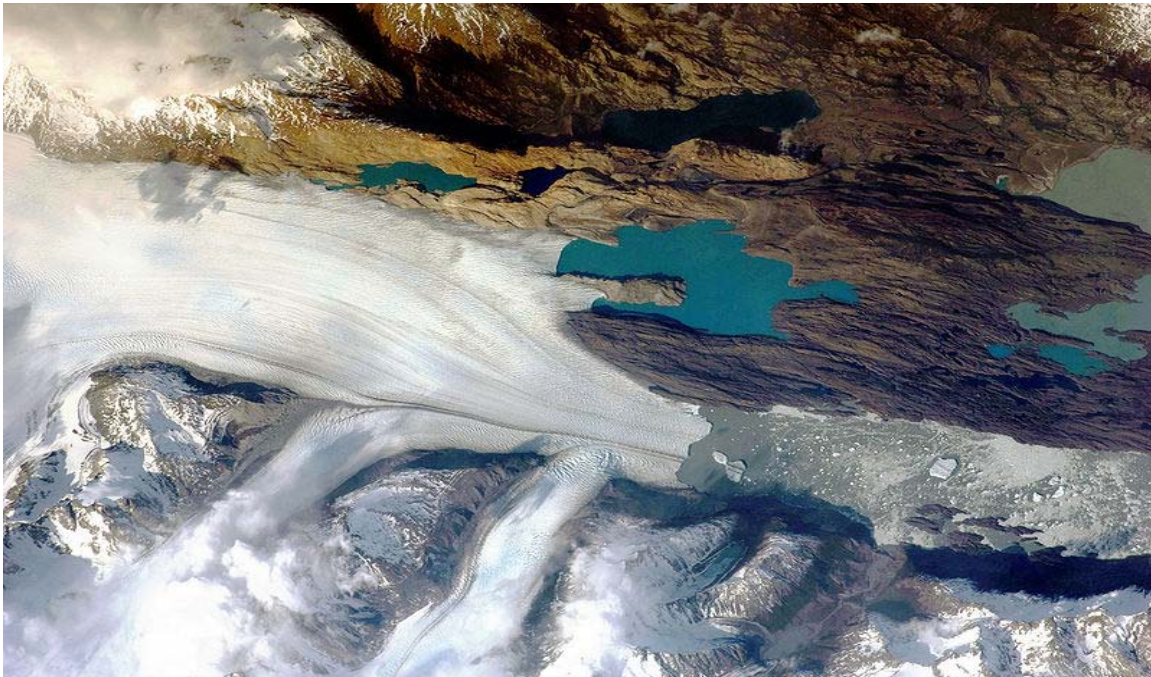
The term “erratic” is commonly used to refer to erratic blocks, which Geikie describes as: “are large masses of rock, often as big as a house, what have been transport by glacier-ice, and have been lodged in a prominent position in the glacier valleys or have been scattered over hills and plains. And examination of their mineralogical character leads the identification of their sources...”. In geology, an erratic is material moved by geologic forces from one location to another, usually by a glacier.

Erratics are formed by glacial ice erosion resulting from the movement of ice. Glaciers erode by multiple processes: abrasion/scouring, plucking, ice thrusting and glacially-induced spalling. Glaciers crack pieces of bedrock off in the process of plucking, producing the larger erratics. In an abrasion process, debris in the basal ice scrapes along the bed, polishing and gouging the underlying rocks, similar to sandpaper on wood, producing smaller glacial till. In ice thrusting, the glacier freezes to its bed, then as it surges forward, it moves large sheets of frozen sediment at the base along with the glacier. Glacially-induced spalling occurs when ice lens formation with the rocks below the glacier spall off layers of rock, providing smaller debris which is ground into the glacial basal material to become till.

Evidence supports another option for creation of erratics as well, rock avalanches onto the upper surface of the glacier (supraglacial). Rock avalanche–supraglacial transport occurs when the glacier undercuts a rock face, which fails by avalanche onto the upper surface of the glacier. The characteristics of rock avalanche–supraglacial transport includes:

- Monolithologic composition - a cluster of boulders of similar composition are frequently found in close proximity. Commingling of the multiple lithologies normally present throughout the glaciated basin, has not occurred.
- Angularity - the supraglacially transported rocks tend to be rough and irregular, with no sign of subglacial abrasion. The sides of boulders are roughly planar, suggesting that some surfaces may be original fracture planes.
- Great size - the size distribution of the boulders tends to be skewed toward larger larger boulders than those produced subglacially.
- Surficial positioning of the boulders - the boulders are positioned on the surface of glacial deposits, as opposed to partially or totally buried.
- Restricted areal extents - the boulder fields tend to have limited areal extent; the boulders cluster together, consistent with the boulders landing on the surface of the glacier and subsequently deposited on top of the glacial drift.
- Orientations - the boulders may be close enough that original fracture planes can be matched.
- Locations of the boulder trains - the boulders appear in rows, trains or clusters along the lateral moraines as opposed to being located on the terminal moraine or in the general glacial field.

Glacier-borne erratic

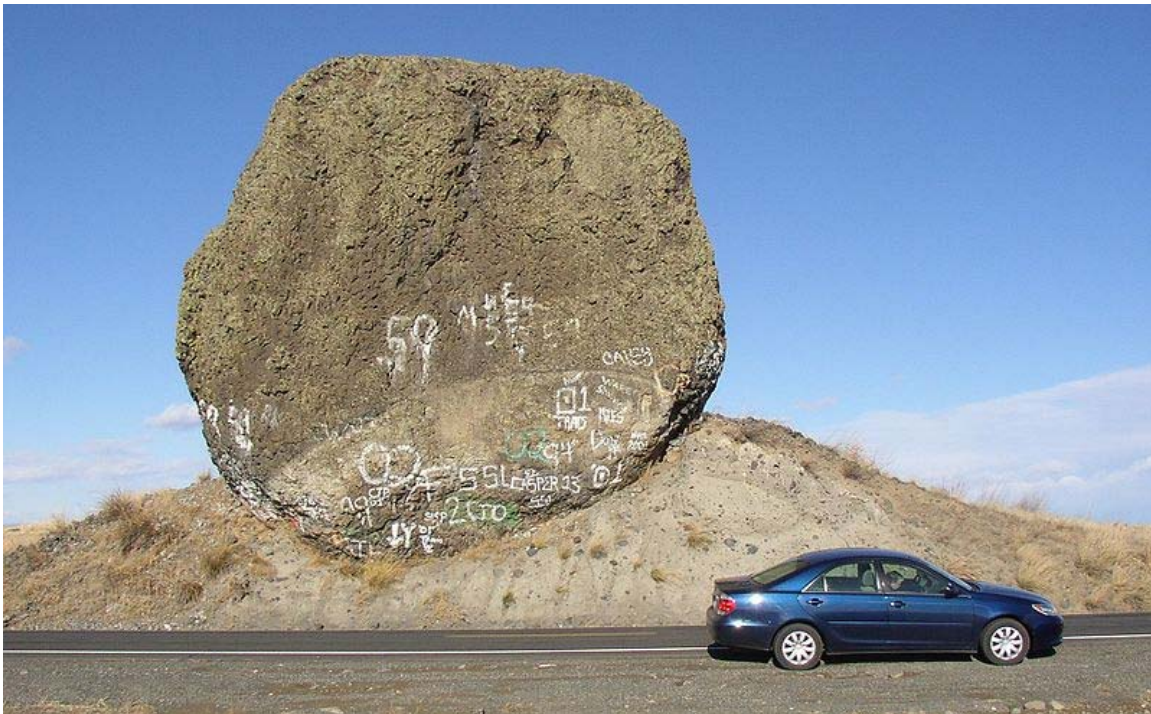


Two icebergs clearly retain fragments of the moraine (rock debris) that forms a dark line along the upper surface of the glacier. The inclusion of the moraine illustrates how land-based rocks and sediment are carried by ice.

Erratics provide an important tool in characterizing the directions of glacier flows, which are routinely reconstructed using a combination of moraines, eskers, drumlins, meltwater channels, and similar data. Erratic distributions and glacial till properties allow for identification of the source rock from which they derive, which confirms the flow direction, particularly when the erratic source outcrop is unique to a limited locality. Erratic materials may be transported by multiple glacier flows prior to their deposition, which can complicate the reconstruction of the glacial flow.

Ice-rafted erratic

Glacial ice entrains debris of varying sizes from small particles to extremely large masses of rock. This debris is transported to the coast by glacier ice and released during the production, drift and melting of icebergs. The rate of debris release by ice depends upon the size of the ice mass in which it is carried as well as the temperature of the ocean through which the ice floe passes.



Yeager Rock, a 400 ton erratic on the Waterville Plateau, Washington. Note the glacial till below the rock.

Sediments from the late Pleistocene period lying on the floor of the North Atlantic show a series of layers (referred to as Heinrich layers) which contain ice-rafted debris. They were formed between 14,000 & 70,000 years before the present. The deposited debris can be traced back to the origin by both the nature of the materials released and the continuous path of debris release. Some paths extend more than 3,000 km distant from the point at which the ice floes originally broke free.

The location and altitude of ice-rafted boulders relative to the modern landscape has been used to identify the highest level of water in proglacial lakes (e.g., Lake Musselshell in central Montana) and temporary lakes (e.g., Lake Lewis in Washington state). Ice-rafted debris is deposited when the iceberg strands on the shore and subsequently melts, or drops out of the ice floe as it melts. Hence all erratic deposits are deposited below the actual high water level of the lake; however the measured altitude of ice-rafted debris can be used to estimate the lake surface elevation.



Angular glacial erratic on Lembert Dome

This is accomplished by recognizing that on a fresh-water lake, the iceberg floats until the volume of its ice-rafted debris exceeds 5% of the volume of the iceberg. Therefore, a correlation between the iceberg size and the boulder size can be established. For example 1.5 m diameter boulder can be carried by a 3 meter high iceberg and could be found stranded at higher elevations than a 2 m boulder which requires a 4 meter high iceberg.

Large erratics



Glacial erratic Ehalkivi with overground volume 930m³ (weight ca 2500 tons) in Estonia



Area exposed by the retreat of Alaska's Steller Glacier in August 1996, the western-most part of Bering Glacier's piedmont lobe. The ground surface is covered by glacial sediment deposited as lodgement and ablation till. The erratic is an angular, ~ 20-ft-high piece of gneiss. Bering Glacier, Alaska flows through Wrangell-Saint Elias National Park

Large erratics consisting of slabs of bedrock that have been lifted and transported by glacier ice to subsequently be stranded above thin glacial or fluvioglacial deposits are referred to as glacial floes, rafts (schollen) or erratic megablocks. Erratic megablocks have typical length to thickness ratios on the order of 100 to 1. These megablocks may be found partially exposed or completely buried by till and are clearly allochthonous, since they overlay glacial till. Megablocks can be so large that they are mistaken for bedrock until underlying glacial or fluvial sediments are identified by drilling or excavation. Such erratic megablocks greater than 1 km² in area and 30 meters in thickness can be found on the Canadian prairies, Poland, England, Denmark and Sweden. One erratic megablock located in Saskatchewan is 30 km by 38 km and up to 100 m thick. Their sources can be identified by locating the bedrock from which they were separated; several rafts from Poland and Alberta were determined to have been transported over 300 km from their source.

Nonglacial erratics

In geology an erratic is any material which is not native to the immediate locale, but has been transported from elsewhere. The most common examples of erratics are associated with glacial transport, either by direct glacier-borne transport or by ice rafting. However other erratics have been identified as the result of kelp holdfasts, which have been documented to transport rocks up to 40 cm in diameter, rocks entangled in the roots of drifting logs, and even in transport of stones accumulated in the stomachs of pinnipeds during foraging.

History

Erratics were once considered evidence of a vast flood approximately 10,000 years ago, similar to the legendary floods described in the texts of ancient civilizations throughout the world. Ancient legends of an epic flood come from many cultures including Mesoamerican, Sumerian (Epic of Gilgamesh), Hebrew (Old Testament) and Indian culture. In the 19th century, many scientists came to favor erratics as evidence for the end of the last glacial maximum (ice age) 10,000 years ago, rather than a flood. Geologists have suggested that landslides or rockfalls initially dropped the rocks on top of glacial ice. The glaciers continued to move, carrying the rocks with them. When the ice melted, the erratics were left in their present locations.

Charles Lyell's *Principles of Geology* (v. 1, 1830) provided an early description of the erratic which is consistent with the modern understanding.

Charles Darwin published extensively on geologic phenomena including the distribution of erratic boulders. In his accounts written during the voyage of HMS Beagle, Darwin observed a number of large erratic boulders of notable size south of the Strait of Magellan, Tierra del Fuego and attributed them to ice rafting from Antarctica. Recent research suggests that they are more likely the result of glacial ice flows carrying the boulders to their current locations.

Examples

Glacier-borne erratics



Example of mixed erratics. The boulder in the foreground is basalt. The boulder across the fence is granite.

The largest known Glacial erratic is Big Rock near Okotoks, Alberta, Canada. Other examples of glacial erratics include:

- Bleasdell Boulder, southern Ontario was described "glacial" in origin by Reverend William Bleasdell in 1872
- A fern-covered erratic the size of a garage is found on Cougar Mountain near Seattle.
- White Rock, British Columbia gets its name from a coastal erratic the size of a garage found on the beach at Semiahmoo Bay, right at the border with Washington.
- The Foothills Erratics Train is a deposit of rocks of many sizes. These deposits stretch in a narrow belt for about 600 km (400 miles) from Alberta's Athabasca River Valley to the southwest of the province.
- Doane Rock, the largest exposed boulder in Cape Cod.
- Madison Boulder, a 5,000 ton glacial erratic the size of a small house in Madison, New Hampshire.

- The northern portion of the town of Waterville, Washington has a large number of large basalt erratics, particularly along the moraine running east-west from McNeil Canyon.

Flood-borne erratics

In the event that glacial ice is "rafted" by a flood such as that created when the ice dam broke during the Missoula Floods, the erratics are deposited where the ice finally releases its debris load. One of the more unusual examples is found far from its origin in Idaho at Erratic Rock State Natural Site just outside McMinnville, Oregon. The park includes a 40-ton specimen, the largest erratic found in the Willamette Valley.

Chapter- 5

Last Glacial Period

The **last glacial period** was the most recent glacial period within the current ice age occurring during the last years (from ≈ 110 ka to 10 ka ago) of the Pleistocene.

During this period there were several changes between glacier advance and retreat. The maximum extent of glaciation was approximately 18,000 years ago. While the general pattern of global cooling and glacier advance was similar, local differences in the development of glacier advance and retreat make it difficult to compare the details from continent to continent.

From the point of view of human evolution, it sets apart the periods paleolithic and mesolithic.



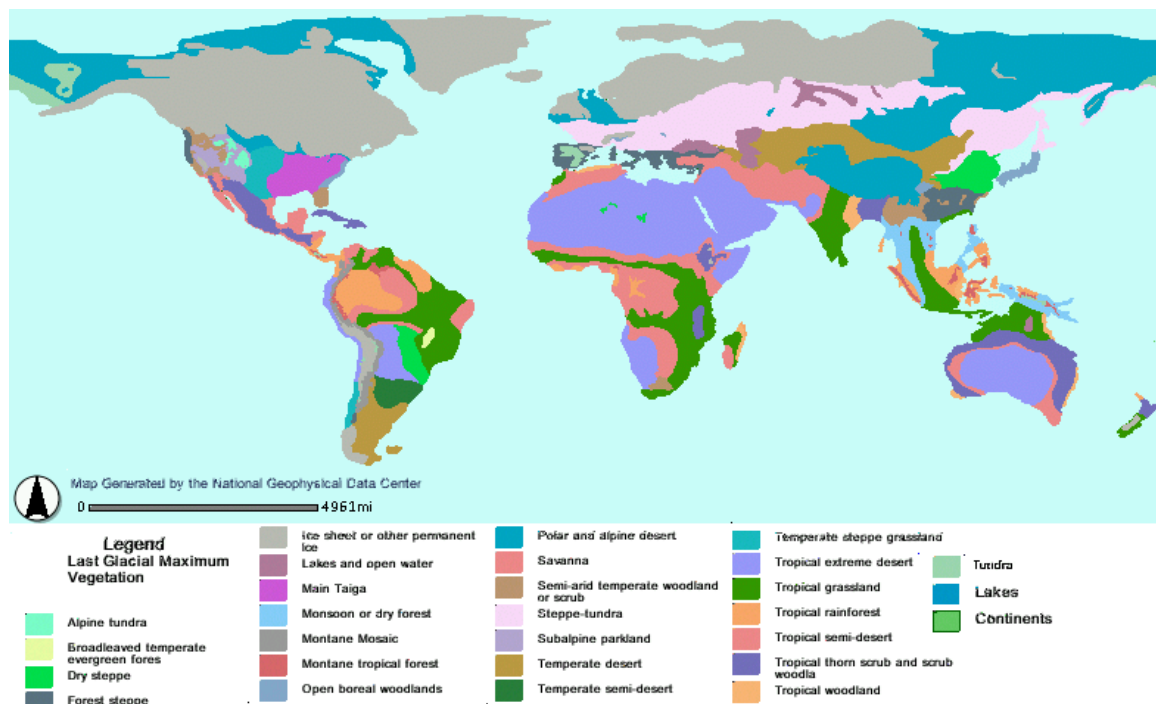
An artist's impression of the last glacial period at glacial maximum. Based on: "Ice age terrestrial carbon changes revisited" by Thomas J. Crowley (Global Biogeochemical Cycles, Vol. 9, 1995, pp. 377–389

Origin and definition

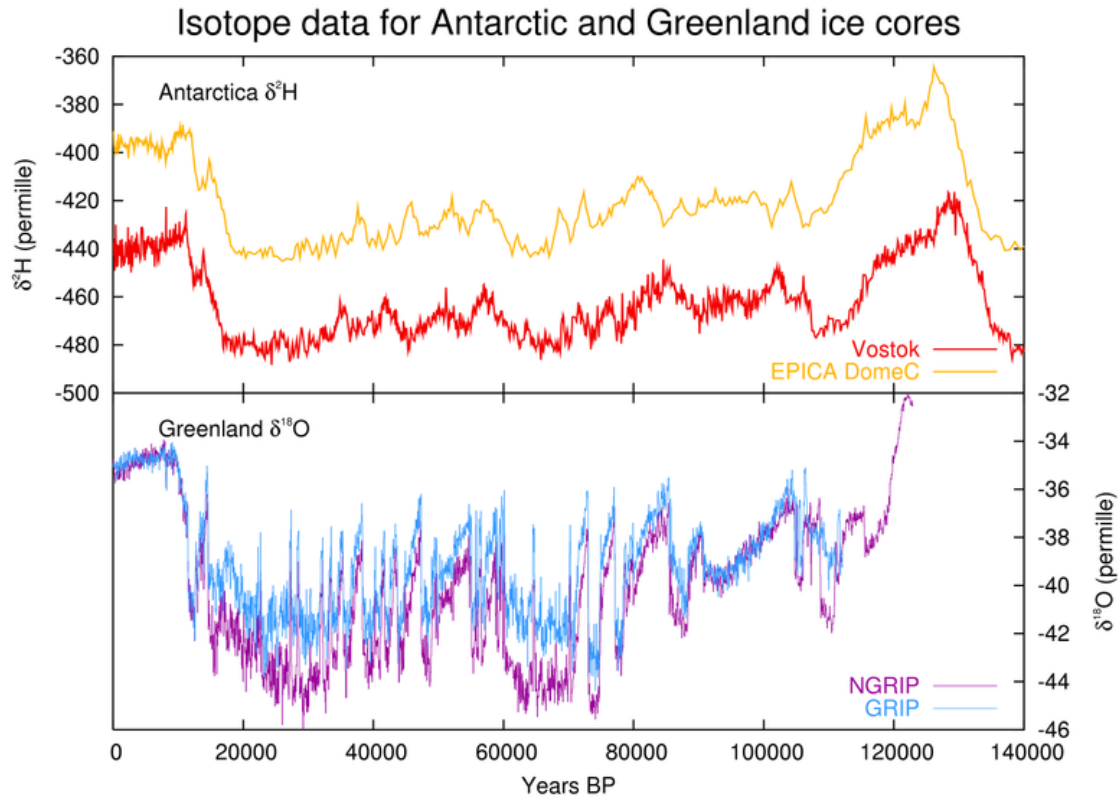
The last glacial period is sometimes colloquially referred to as the "last ice age", though this use is incorrect because an ice age is a longer period of cold temperature in which ice sheets cover large parts of the Earth, such as Antarctica. Glacials, on the other hand, refer to colder phases within an ice age that separate interglacials. Thus, the end of the last glacial period is not the end of the last ice age. The end of the last glacial period was about 12,500 years ago, while the end of the last ice age may not yet have come: little evidence points to a stop of the glacial-interglacial cycle of the last million years.

The last glacial period is the best-known part of the current ice age, and has been intensively studied in North America, northern Eurasia, the Himalaya and other formerly glaciated regions around the world. The glaciations that occurred during this glacial period covered many areas, mainly on the Northern Hemisphere and to a lesser extent on the Southern Hemisphere. They have different names, historically developed and depending on their geographic distributions: **Fraser** (in the Pacific Cordillera of North America), **Pinedale**, **Wisconsinan** or **Wisconsin** (in central North America), **Devensian** (in the British Isles), **Midlandian** (in Ireland), **Würm** (in the Alps), **Mérida** (in Venezuela), **Weichselian** (in Scandinavia and Northern Europe), **Vistulian** (in northern Central Europe), **Valdai** in Eastern Europe and **Zyryanka** in Siberia, **Llanquihue** in Chile, and **Otira** in New Zealand.

Overview



Vegetation types at time of last glacial maximum



Last glacial period, as seen in ice core data from Antarctica and Greenland

The last glaciation centered on the huge ice sheets of North America and Eurasia. Considerable areas in the Alps, the Himalaya and the Andes were ice-covered, and Antarctica remained glaciated.

Canada was nearly completely covered by ice, as well as the northern part of the USA, both blanketed by the huge Laurentide ice sheet. Alaska remained mostly ice free due to arid climate conditions. Local glaciations existed in the Rocky Mountains and the Cordilleran ice sheet and as ice fields and ice caps in the Sierra Nevada in northern California. In Britain, mainland Europe, and northwestern Asia, the Scandinavian ice sheet once again reached the northern parts of the British Isles, Germany, Poland, and Russia, extending as far east as the Taimyr Peninsula in western Siberia. Maximum extent of western Siberian glaciation was approximately 18,000 to 17,000 BP and thus later than in Europe (22,000–18,000 BP). Northeastern Siberia was not covered by a continental-scale ice sheet. Instead, large, but restricted, icefield complexes covered mountain ranges within northeast Siberia, including the Kamchatka-Koryak Mountains.

The Arctic Ocean between the huge ice sheets of America and Eurasia was not frozen throughout, but like today probably was only covered by relatively shallow ice, subject to seasonal changes and riddled with icebergs calving from the surrounding ice sheets. According to the sediment composition retrieved from deep-sea cores there must even have been times of seasonally open waters.

Outside the main ice sheets, widespread glaciation occurred on the Alps-Himalaya mountain chain. In contrast to the earlier glacial stages, the Würm glaciation was composed of smaller ice caps and mostly confined to valley glaciers, sending glacial lobes into the Alpine foreland. To the east the Caucasus and the mountains of Turkey and Iran were capped by local ice fields or small ice sheets. In the Himalaya and the Tibetan Plateau, glaciers advanced considerably, particularly between 47,000–27,000 BP and in contrast to the widespread contemporaneous warming elsewhere. The formation of a contiguous ice sheet on the Tibetan Plateau is controversial.

Other areas of the Northern Hemisphere did not bear extensive ice sheets but local glaciers in high areas. Parts of Taiwan for example were repeatedly glaciated between 44,250 and 10,680 BP as well as the Japanese Alps. In both areas maximum glacier advance occurred between 60,000 and 30,000 BP (starting roughly during the Toba catastrophe). To a still lesser extent glaciers existed in Africa, for example in the High Atlas, the mountains of Morocco, the Mount Atakor massif in southern Algeria, and several mountains in Ethiopia. In the Southern Hemisphere, an ice cap of several hundred square kilometers was present on the east African mountains in the Kilimanjaro Massif, Mount Kenya and the Ruwenzori Mountains, still bearing remnants of glaciers today.

Glaciation of the Southern Hemisphere was less extensive because of current configuration of continents. Ice sheets existed in the Andes (Patagonian Ice Sheet), where six glacier advances between 33,500 and 13,900 BP in the Chilean Andes have been reported. Antarctica was entirely glaciated, much like today, but the ice sheet left no uncovered area. In mainland Australia only a very small area in the vicinity of Mount Kosciuszko was glaciated, whereas in Tasmania glaciation was more widespread. New Zealand saw a glaciation in the New Zealand Alps, where at least three glacier advances can be distinguished. Local ice caps existed in Irian Jaya, Indonesia, where in three ice areas remnants of the Pleistocene glaciers are still preserved today.

Named local glaciations

Pinedale or Fraser glaciation, in the Rocky Mountains, USA

The Pinedale (central Rocky Mountains) or Fraser (Cordilleran ice sheet) glaciation was the last of the major glaciations to appear in the Rocky Mountains in the United States. The Pinedale lasted from approximately 30,000 to 10,000 years ago and was at its greatest extent between 23,500 and 21,000 years ago. This glaciation was somewhat distinct from the main Wisconsin glaciation as it was only loosely related to the giant ice sheets and was instead composed of mountain glaciers, merging into the Cordilleran Ice Sheet. The Cordilleran ice sheet produced features such as glacial Lake Missoula, which would break free from its ice dam causing the massive Missoula floods. Geologists estimate that the cycle of flooding and reformation of the lake lasted on average of 55 years and that the floods occurred approximately 40 times over the 2,000 year period between 15,000 and 13,000 years ago. Glacial lake outburst floods such as these are not uncommon today in Iceland and other places.

Wisconsin glaciation, in North America

The Wisconsin Glacial Episode was the last major advance of continental glaciers in the North American Laurentide ice sheet. This glaciation is made of three glacial maxima separated by interglacial warm periods (such as the one we are living in). These glacial maxima are called, from oldest to newest, *Tahoe*, *Tenaya*, and *Tioga*. The Tahoe reached its maximum extent perhaps about 70,000 years ago, perhaps as a byproduct of the Toba super eruption. Little is known about the Tenaya. The Tioga was the least severe and last of the Wisconsin Episode. It began about 30,000 years ago, reached its greatest advance 21,000 years ago, and ended about 10,000 years ago. At the height of glaciation the Bering land bridge permitted migration of mammals such as humans to North America from Siberia.

It radically altered the geography of North America north of the Ohio River. At the height of the Wisconsin Episode glaciation, ice covered most of Canada, the Upper Midwest, and New England, as well as parts of Montana and Washington. On Kelleys Island in Lake Erie or in New York's Central Park, the grooves left by these glaciers can be easily observed. In southwestern Saskatchewan and southeastern Alberta a suture zone between the Laurentide and Cordilleran ice sheets formed the Cypress Hills, which is the northernmost point in North America that remained south of the continental ice sheets.

The Great Lakes are the result of glacial scour and pooling of meltwater at the rim of the receding ice. When the enormous mass of the continental ice sheet retreated, the Great Lakes began gradually moving south due to isostatic rebound of the north shore. Niagara Falls is also a product of the glaciation, as is the course of the Ohio River, which largely supplanted the prior Teays River.

With the assistance of several very broad glacial lakes, it carved the gorge now known as the Upper Mississippi River, filling into the Driftless Area and probably creating an annual ice-dam-burst.

In its retreat, the Wisconsin Episode glaciation left terminal moraines that form Long Island, Block Island, Cape Cod, Nomans Land, Marthas Vineyard, Nantucket, Sable Island and the Oak Ridges Moraine in south central Ontario, Canada. In Wisconsin itself, it left the Kettle Moraine. The drumlins and eskers formed at its melting edge are landmarks of the Lower Connecticut River Valley.

Greenland glaciation

In Northwest Greenland, ice coverage attained a very early maximum in the last glacial period around 114,000. After this early maximum, the ice coverage was similar to today until the end of the last glacial period. Towards the end glaciers readvanced once more before retreating to their present extent. According to ice core data, the Greenland climate was dry during the last glacial period, precipitation reaching perhaps only 20% of today's value.

Devensian & Midlandian glaciation, in Britain and Ireland

The name **Devensian glaciation** is used by British geologists and archaeologists and refers to what is often popularly meant by the latest Ice Age. Irish geologists, geographers, and archaeologists refer to the **Midlandian** glaciation as its effects in Ireland are largely visible in the Irish Midlands.

The effects of this glaciation can be seen in many geological features of England, Wales, Scotland, and Northern Ireland. Its deposits have been found overlying material from the preceding Ipswichian Stage and lying beneath those from the following Flandrian stage of the Holocene.

The latter part of the Devensian includes Pollen zones I-IV, the Allerød and Bølling Oscillations, and the Older and Younger Dryas climatic stages.

Weichselian glaciation, in Scandinavia and northern Europe

Alternative names include: Weichsel or Vistulian glaciation (named after the Polish river Vistula or its German name Weichsel). During the glacial maximum in Scandinavia, only the western parts of Jutland were ice-free, and a large part of what is today the North Sea was dry land connecting Jutland with Britain. It is also in Denmark that the only Scandinavian ice-age animals older than 13,000 BC are found. In the period following the last interglacial before the current one (Eemian Stage), the coast of Norway was also ice-free.

The Baltic Sea, with its unique brackish water, is a result of meltwater from the Weichsel glaciation combining with saltwater from the North Sea when the straits between Sweden and Denmark opened. Initially, when the ice began melting about 10,300 ybp, seawater filled the isostatically depressed area, a temporary marine incursion that geologists dub the Yoldia Sea. Then, as post-glacial isostatic rebound lifted the region about 9500 ybp, the deepest basin of the Baltic became a freshwater lake, in palaeological contexts referred to as Ancylus Lake, which is identifiable in the freshwater fauna found in sediment cores. The lake was filled by glacial runoff, but as worldwide sea level continued rising, saltwater again breached the sill about 8000 ybp, forming a marine Littorina Sea which was followed by another freshwater phase before the present brackish marine system was established. "At its present state of development, the marine life of the Baltic Sea is less than about 4000 years old," Drs. Thulin and Andrushaitis remarked when reviewing these sequences in 2003.

Overlying ice had exerted pressure on the Earth's surface. As a result of melting ice, the land has continued to rise yearly in Scandinavia, mostly in northern Sweden and Finland where the land is rising at a rate of as much as 8–9 mm per year, or 1 meter in 100 years. This is important for archaeologists since a site that was coastal in the Nordic Stone Age now is inland and can be dated by its relative distance from the present shore.

Würm glaciation, in the Alps

The term *Würm* is derived from a river in the Alpine foreland, approximately marking the maximum glacier advance of this particular glacial period. The Alps have been the area where first systematic scientific research on ice ages has been conducted by Louis Agassiz in the beginning of the 19th century. Here the Würm glaciation of the last glacial period was intensively studied. Pollen analysis, the statistical analyses of microfossilized plant pollens found in geological deposits, has chronicled the dramatic changes in the European environment during the Würm glaciation. During the height of Würm glaciation, *ca* 24,000–10,000 ybp, most of western and central Europe and Eurasia was open steppe-tundra, while the Alps presented solid ice fields and montane glaciers. Scandinavia and much of Britain were under ice.

During the Würm, the Rhône Glacier covered the whole western Swiss plateau, reaching today's regions of Solothurn and Aarau. In the region of Bern it merged with the Aar glacier. The Rhine Glacier is currently the subject of the most detailed studies. Glaciers of the Reuss and the Limmat advanced sometimes as far as the Jura. Montane and piedmont glaciers formed the land by grinding away virtually all traces of the older Günz and Mindel glaciation, by depositing base moraines and terminal moraines of different retraction phases and loess deposits, and by the pro-glacial rivers' shifting and redepositing gravels. Beneath the surface, they had profound and lasting influence on geothermal heat and the patterns of deep groundwater flow.

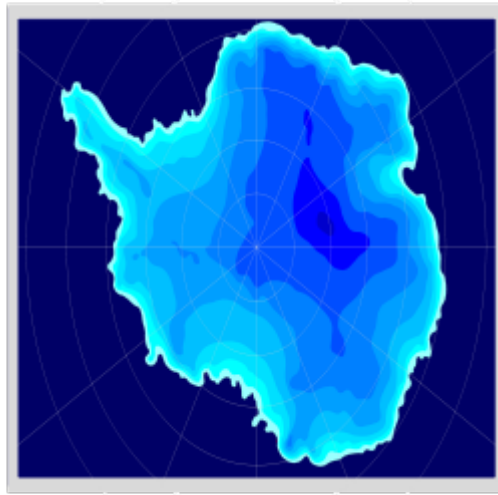
Merida glaciation, in the Venezuelan Andes

The name *Mérida* Glaciation is proposed to designate the alpine glaciation which affected the central Venezuelan Andes; during the Late Pleistocene. Two main moraine levels have been recognized: one between 2600 and 2700 m, and another between 3000 and 3500 m elevation. The snow line during the last glacial advance was lowered approximately 1200 m below the present snow line (3700 m). The glaciated area in the Cordillera de Mérida was approximately 600 km²; this included the following high areas from southwest to northeast: Páramo de Tamá, Páramo Batallón, Páramo Los Conejos, Páramo Piedras Blancas, and Teta de Niquitao. Approximately 200 km² of the total glaciated area was in the Sierra Nevada de Mérida, and of that amount, the largest concentration, 50 km², was in the areas of Pico Bolívar, Pico Humboldt (4,942 m), and Pico Bonpland (4,893 m). Radiocarbon dating indicates that the moraines are older than 10,000 years B.P., and probably older than 13,000 years B.P. The lower moraine level probably corresponds to the main Wisconsin glacial advance. The upper level probably represents the last glacial advance (Late Wisconsin).

Llanquihue glaciation, southern Andes

The Llanquihue glaciation takes its name from Llanquihue Lake in southern Chile which is a fan-shaped piedmont glacial lake. On the lake's western shores there are large moraine systems of which the innermost belong to the last glacial period. Llanquihue Lake's varves are a node point in southern Chile's varve geochronology. During the last

glacial maximum the Patagonian Ice Sheet extended over the Andes from about 35°S to Tierra del Fuego at 55°S. The western part appears to have been very active, with wet basal conditions, while the eastern part was cold based. Palsas seems to have developed at least in the unglaciated parts of Isla Grande de Tierra del Fuego. The area west of Llanquihue Lake was ice-free during the LGM, and had sparsely distributed vegetation dominated by Nothofagus. Valdivian temperate rainforest was reduced to scattered remnants in the western side of the Andes.



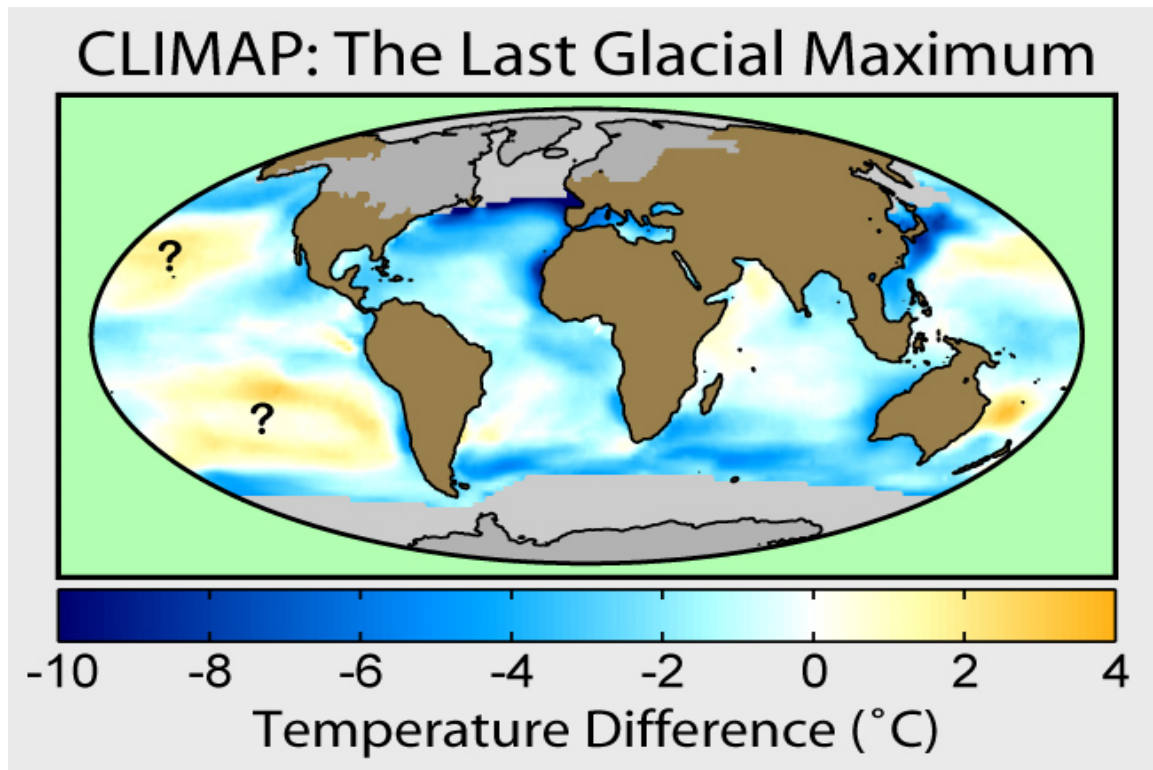
Modelled maximum extent of the Antarctic ice sheet 21,000 years before present

Lake Pippa was also affected by the Pleistocene, a glacier ripped through the center of it causing a very deep lake in the south atlantic.

Antarctica glaciation

During the last glacial period Antarctica was blanketed by a massive ice sheet, much like it is today. The ice covered all land areas and extended into the ocean onto the middle and outer continental shelf. According to ice modelling, ice over central East Antarctica was generally thinner than today.

Last Glacial Maximum



Map of sea surface temperature changes and glacial extent during the last glacial maximum according to the CLIMAP project.

The **Last Glacial Maximum (LGM)** refers to the time of maximum extent of the ice sheets during the last glacial period, approximately 20,000 years ago. This extreme persisted for several thousand years. It was followed by the Late Glacial Maximum.

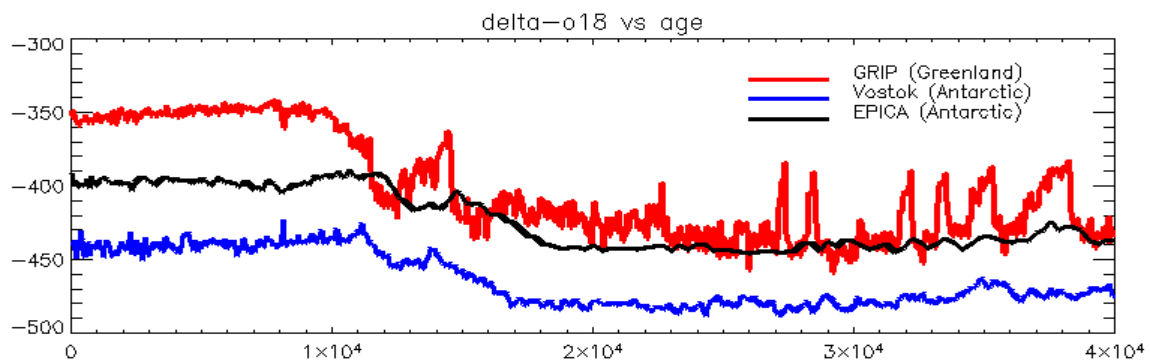
At this time, ice sheets covered the whole of Iceland and all but the southern extremity of the British Isles. Northern Europe was largely covered, the southern boundary passing through Germany and Poland, but not quite joined to the British ice sheet. This ice extended northward to cover Svalbard and Franz Josef Land and eastward to occupy the northern half of the West Siberian Plain, ending at the Taymyr Peninsula, and damming the Ob and Yenisei rivers forming a West Siberian Glacial Lake. In North America, the ice covered essentially all of Canada and extended roughly to the Missouri and Ohio Rivers, and eastward to New York City.

In the Southern Hemisphere, the Patagonian Ice Sheet covered Chile and western Argentina north to about 41 degrees south. Ice sheets also covered Tibet (scientists continue to debate the extent to which the Tibetan Plateau was covered with ice), Baltistan, Ladakh, the Venezuelan Andes and the Andean altiplano. In Africa, the Middle East and Southeast Asia, many smaller mountain glaciers formed, especially in the Atlas, the Bale Mountains, and New Guinea.

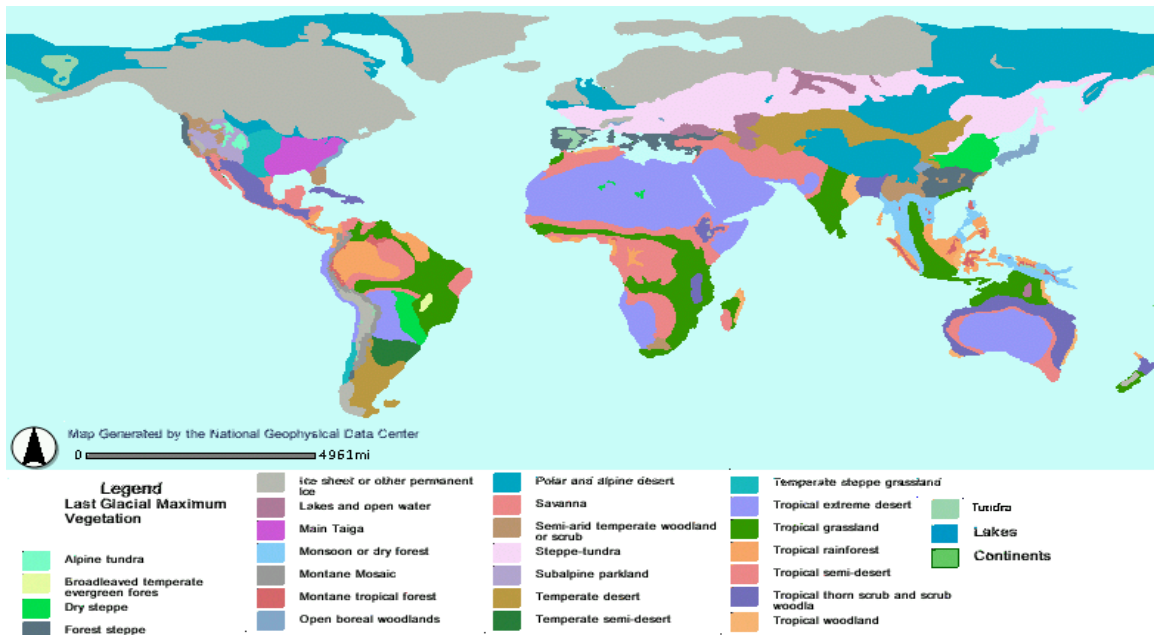
Permafrost covered Europe south of the ice sheet down to present-day Szeged and Asia down to Beijing. In North America, latitudinal gradients were so sharp that permafrost did not reach far south of the ice sheets except at high elevations.

The Indonesian islands as far east as Borneo and Bali were connected to the Asian continent in a landmass called Sundaland. Palawan was also part of Sundaland, while the rest of the Philippine Islands formed one large island separated from the continent only by the Sibutu Passage and the Mindoro Strait. Australia and New Guinea were connected forming Sahulland. Between Sundaland and Sahulland, Wallacea remained islands, though the number and width of water gaps between the two continents were considerably smaller.

Glacial climate



Temperature proxies for the last 40,000 years



Map of vegetation patterns during the last glacial maximum

The formation of an ice sheet or ice cap requires both prolonged cold and precipitation (snow). Hence, despite having temperatures similar to those of glaciated areas in North America and Europe, East Asia and parts of Alaska remained *unglaciated* except at higher elevations. This difference was caused by the fact that the ice sheets in Europe produced extensive anticyclones above them. These anticyclones generated air masses that were so dry on reaching Siberia and Manchuria that precipitation sufficient for the formation of glaciers could never occur (except in Kamchatka where these westerly winds lifted moisture from the Sea of Japan). The relative warmth of the Pacific Ocean due to the shutting down of the Oyashio Current and the presence of large *east-west* mountain ranges were secondary factors preventing continental glaciation in Asia.

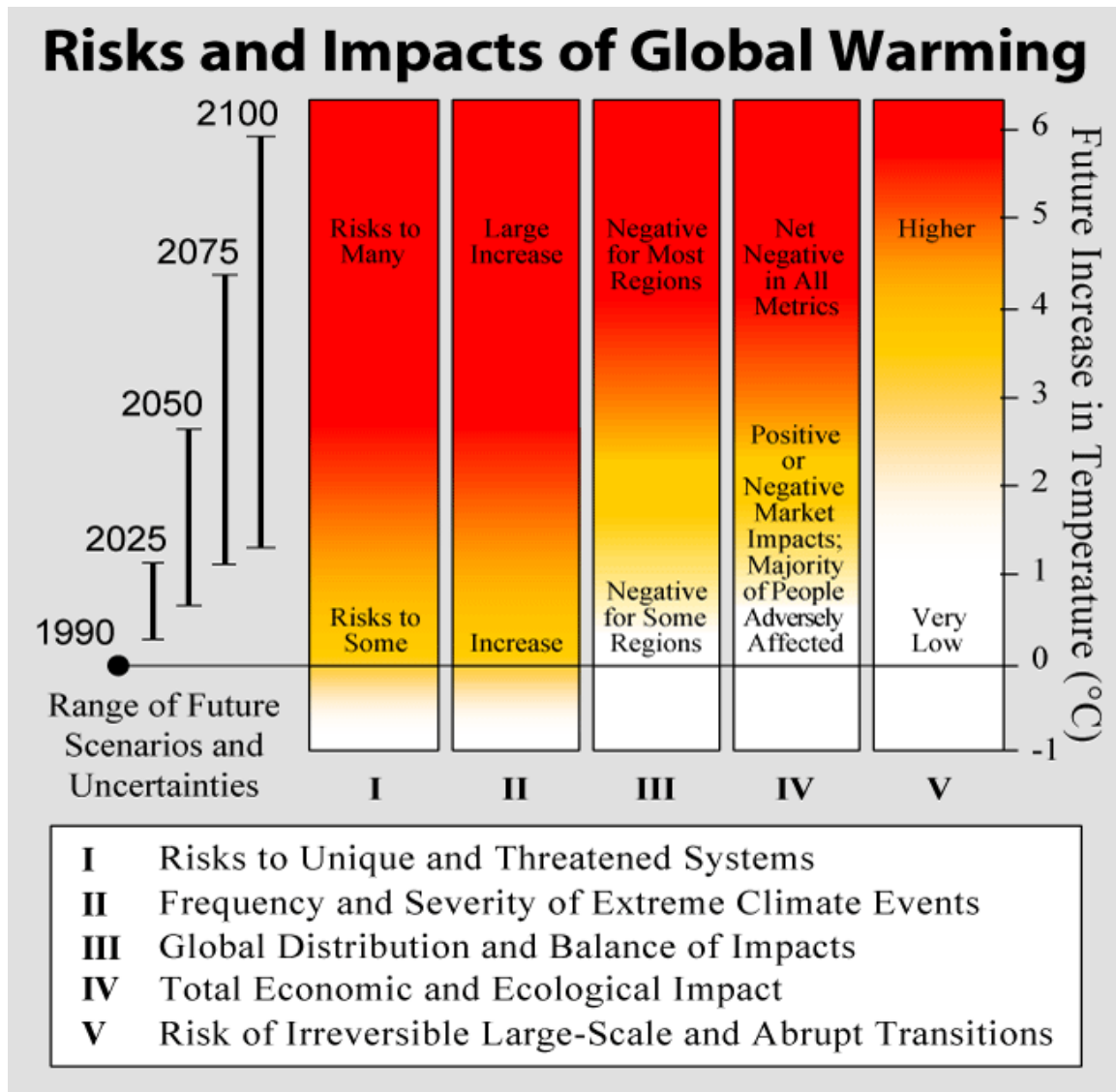
In warmer regions of the world, climates at the Last Glacial Maximum were cooler and almost everywhere drier. In extreme cases, such as South Australia and the Sahel, rainfall could be diminished by up to ninety percent from present, with floras diminished to almost the same degree as in glaciated areas of Europe and North America. Even in less affected regions, rainforest cover was greatly diminished, especially in West Africa where a few *refugia* were surrounded by tropical grassland. The Amazon rainforest was split into two large blocks by extensive savanna, and it is probable that the tropical rainforests of Southeast Asia were similarly affected, with deciduous forests expanding in their place except on the east and west extremities of the Sundaland shelf. Only in Central America and the Chocó region of Colombia did tropical rainforests remain substantially intact – probably due to the extraordinarily heavy rainfall of these regions.

Most of the world's deserts expanded. Exceptions were in the American West, where changes in the jet stream brought heavy rain to areas that are now desert and large pluvial lakes formed, the best known being Lake Bonneville in Utah. This also occurred in Afghanistan and Iran where a major lake formed in the Dasht-e Kavir. In Australia, shifting sand dunes covered half the continent, whilst the Chaco and Pampas in South America became similarly dry. Present-day subtropical regions also lost most of their forest cover, notably in eastern Australia, the Atlantic Forest of Brazil, and southern China, where open woodland became dominant due to drier conditions. In northern China – unglaciated despite its cold climate – a mixture of grassland and tundra prevailed, and even here, the northern limit of tree growth was at least twenty degrees further south than today.

In the period immediately *before* the Last Glacial Maximum, many areas that became completely barren desert were wetter than they are today, notably in southern Australia where Aboriginal occupation is believed to coincide with a wet period between 40,000 and 60,000 years BP (Before Present, a formal measurement of uncalibrated radiocarbon years, counted from 1950 AD).

Chapter- 6

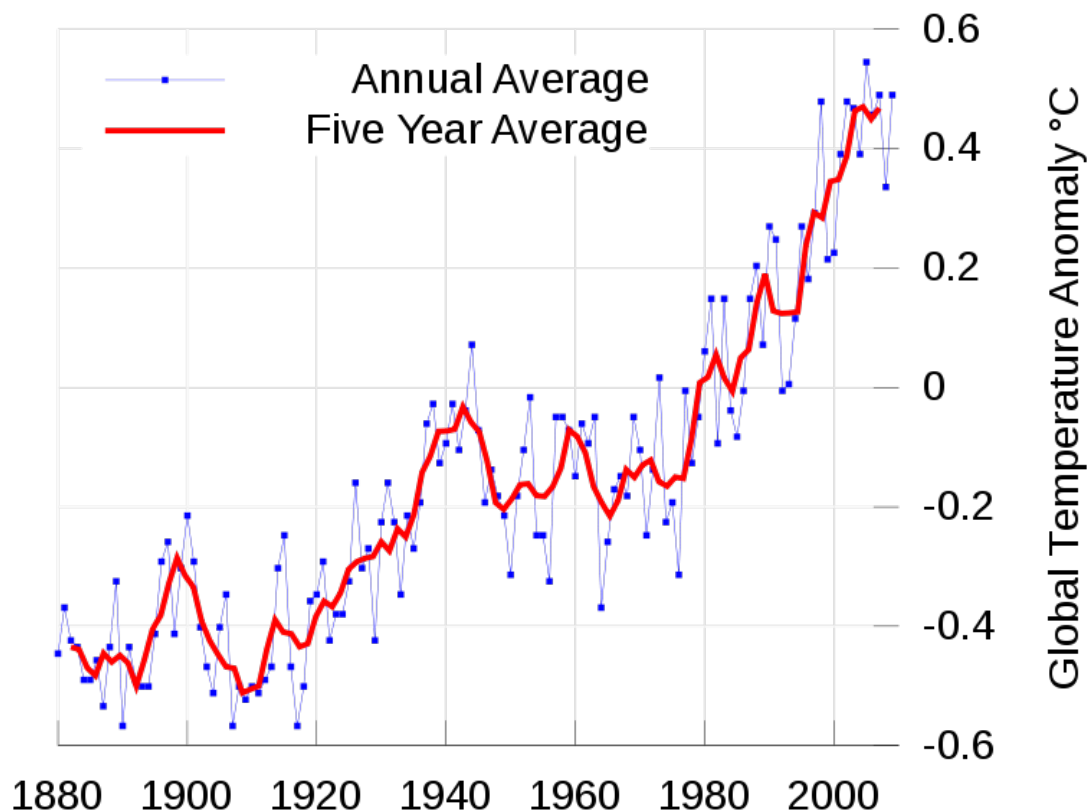
Effects of Global Warming



Graphical description of risks and impacts of climate change by IPCC (2001). A revision of this figure by Smith *et al.* (2009) shows increased risks.

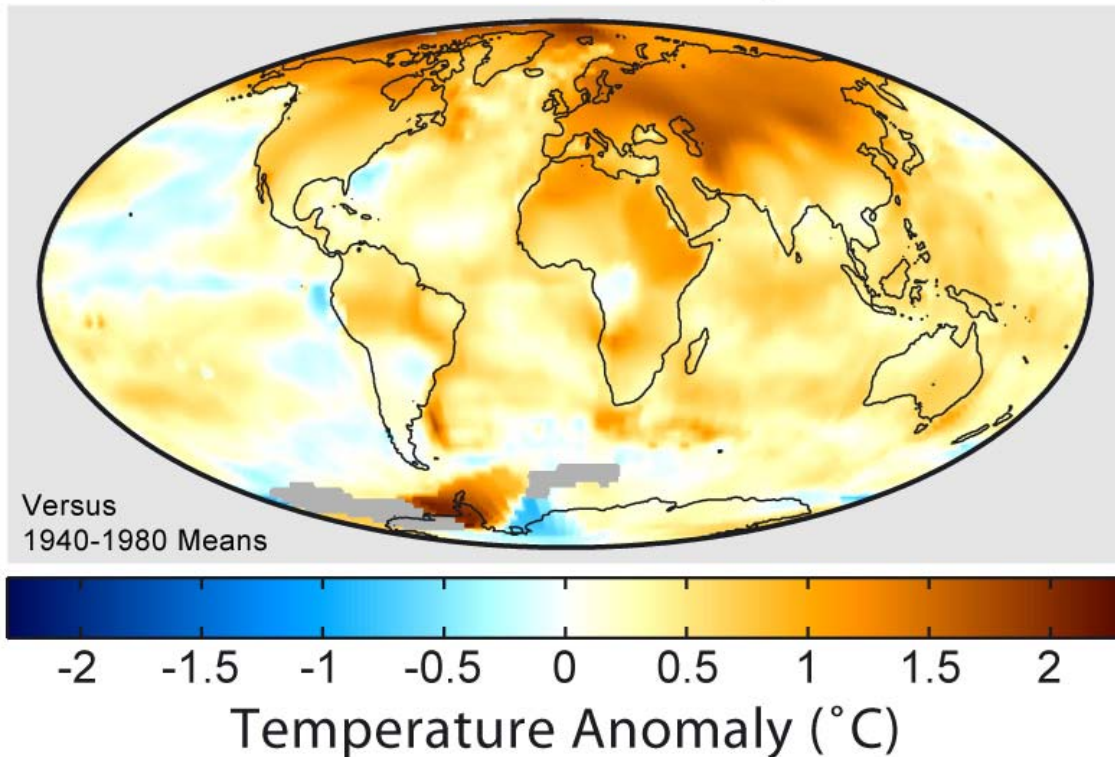
This is about the **effects of global warming** and climate change. The effects, or impacts, of climate change may be physical, ecological, social or economic. Evidence of observed climate change includes the instrumental temperature record, rising sea levels, and decreased snow cover in the Northern Hemisphere. According to IPCC (2007a:10), "[most] of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in [human greenhouse gas] concentrations". It is predicted that future climate changes will include further global warming (i.e., an upward trend in global mean temperature), sea level rise, and a probable increase in the frequency of some extreme weather events. Signatories of the United Nations Framework Convention on Climate Change have agreed to implement policies designed to reduce their emissions of greenhouse gases.

Overview



Global mean surface temperature difference from the average for 1880-2009

1999-2008 Mean Temperatures



Mean surface temperature change for the period 1999 to 2008 relative to the average temperatures from 1940 to 1980

Over the last hundred years or so, the instrumental temperature record has shown a trend in climate of increased global mean temperature, i.e., global warming. Other observed changes include Arctic shrinkage, Arctic methane release, releases of terrestrial carbon from permafrost regions and Arctic methane release in coastal sediments, and sea level rise. Global average temperature is predicted to increase over this century, with a probable increase in frequency of some extreme weather events, and changes in rainfall patterns. Moving from global to regional scales, there is increased uncertainty over how climate will change. The probability of warming having unforeseen consequences increases with the rate, magnitude, and duration of climate change. Some of the physical impacts of climate change are irreversible at continental and global scales. With medium confidence, IPCC (2007b:17) concluded that with a global average temperature increase of 1–4°C, (relative to 1990–2000) partial deglaciation of the Greenland ice sheet would occur over a period of centuries to millennia. Including the possible contribution of partial deglaciation of the West Antarctic Ice Sheet, sea level would rise by 4–6 m or more.

The impacts of climate change across world population will not be distributed evenly (Smith *et al.*, 2001:957). Some regions and sectors are expected to experience benefits while others will experience costs. With greater levels of warming (greater than 2–3°C by

2100, relative to 1990 temperature levels), it is very likely that benefits will decline and costs increase (IPCC, 2007b:17). Low-latitude and less-developed areas are probably at the greatest risk from climate change (Schneider *et al.*, 2007:781). With human systems, adaptation potential for climate change impacts is considerable, although the costs of adaptation are largely unknown and potentially large. In a literature assessment, Schneider *et al.* (2007:792) concluded, with high confidence, that climate change would likely result in reduced diversity of ecosystems and the extinction of many species.

Definition of climate change

This refers to reports produced by the IPCC. In their usage, "climate change" refers to a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties, and that persists for extended periods, typically decades or longer (IPCC, 2007d:30). The climate change referred to may be due to natural causes or the result of human activity.

Physical impacts

This section describes some physical impacts of climate change. For some of these physical impacts, their effect on social and economic systems are also described.

Effects on weather

Increasing temperature is likely to lead to increasing precipitation but the effects on storms are less clear. Extratropical storms partly depend on the temperature gradient, which is predicted to weaken in the northern hemisphere as the polar region warms more than the rest of the hemisphere.

Extreme weather

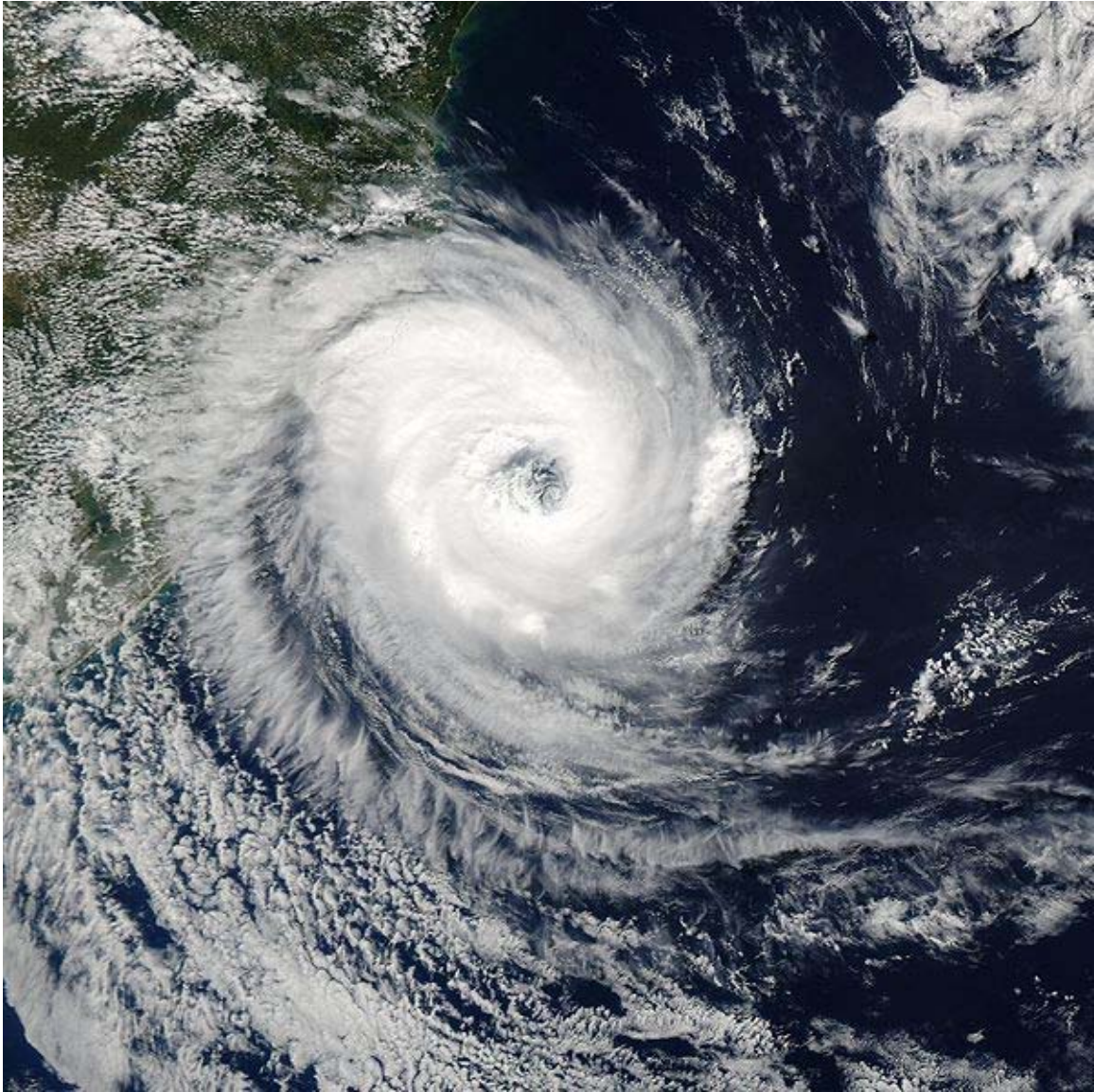
IPCC (2007a:8) predicted that in the future, over most land areas, the frequency of warm spells or heat waves would very likely increase. Other likely changes are listed below:

- Increased areas will be affected by drought
- There will be increased intense tropical cyclone activity
- There will be increased incidences of extreme high sea level (excluding tsunamis)

Increased freshwater flow

Research based on satellite observations, published in October, 2010, shows an increase in the flow of freshwater into the world's oceans, partly from melting ice and partly from increased precipitation driven by an increase in global ocean evaporation. The increase in global freshwater flow, based on data from 1994 to 2006, was about 18%. Much of the increase is in areas which already experience high rainfall. One effect, as perhaps experienced in the 2010 Pakistan floods, is to overwhelm flood control infrastructure.

Local climate change



The first recorded South Atlantic hurricane, "Catarina", which hit Brazil in March 2004

Regional effects of global warming vary in nature. Some are the result of a generalised global change, such as rising temperature, resulting in local effects, such as melting ice. In other cases, a change may be related to a change in a particular ocean current or weather system. In such cases, the regional effect may be disproportionate and will not necessarily follow the global trend.

There are three major ways in which global warming will make changes to regional climate: melting or forming ice, changing the hydrological cycle (of evaporation and precipitation) and changing currents in the oceans and air flows in the atmosphere. The coast can also be considered a region, and will suffer severe impacts from sea level rise.

Biogeochemical cycles

Climate change may have an effect on the carbon cycle in an interactive "feedback" process. A feedback exists where an initial process triggers changes in a second process that in turn influences the initial process. A positive feedback intensifies the original process, and a negative feedback reduces it (IPCC, 2007d:78). Models suggest that the interaction of the climate system and the carbon cycle is one where the feedback effect is positive (Schneider *et al.*, 2007:792).

Using the A2 SRES emissions scenario, Schneider *et al.* (2007:789) found that this effect led to additional warming by 2100, relative to the 1990-2000 period, of 0.1 to 1.5 °C. This estimate was made with high confidence. The climate projections made in the IPCC Fourth Assessment Report of 1.1 to 6.4 °C account for this feedback effect. On the other hand, with medium confidence, Schneider *et al.* (2007) commented that additional releases of GHGs were possible from permafrost, peat lands, wetlands, and large stores of marine hydrates at high latitudes.

Glacier retreat and disappearance

IPCC (2007a:5) found that, on average, mountain glaciers and snow cover had decreased in both the northern and southern hemispheres. This widespread decrease in glaciers and ice caps has contributed to observed sea level rise. With very high or high confidence, IPCC (2007d:11) made a number of predictions relating to future changes in glaciers:

- Mountainous areas in Europe will face glacier retreat
- In Latin America, changes in precipitation patterns and the disappearance of glaciers will significantly affect water availability for human consumption, agriculture, and energy production
- In Polar regions, there will be reductions in glacier extent and the thickness of glaciers.

Oceans

The role of the oceans in global warming is a complex one. The oceans serve as a sink for carbon dioxide, taking up much that would otherwise remain in the atmosphere, but increased levels of CO₂ have led to ocean acidification. Furthermore, as the temperature of the oceans increases, they become less able to absorb excess CO₂. Global warming is projected to have a number of effects on the oceans. Ongoing effects include rising sea levels due to thermal expansion and melting of glaciers and ice sheets, and warming of the ocean surface, leading to increased temperature stratification. Other possible effects include large-scale changes in ocean circulation.

Acidification

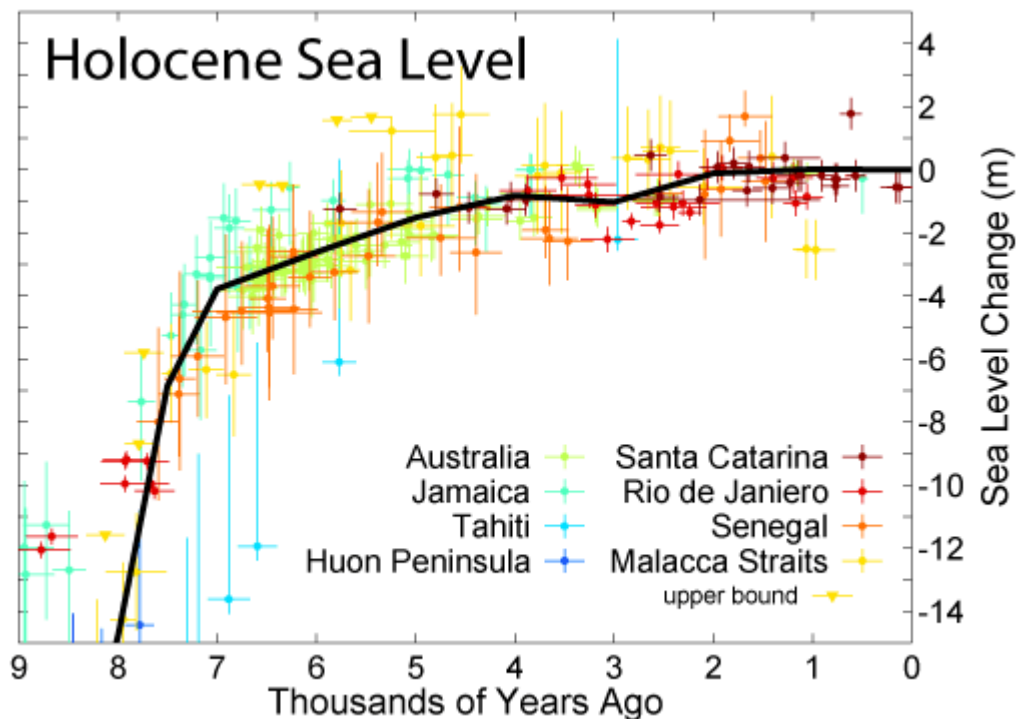
Dissolving CO₂ in seawater increases the hydrogen ion (H⁺) concentration in the ocean, and thus decreases ocean pH. Caldeira and Wickett (2003) placed the rate and magnitude

of modern ocean acidification changes in the context of probable historical changes during the last 300 million years. Since the industrial revolution began, it is estimated that surface ocean pH has dropped by slightly more than 0.1 units (on the logarithmic scale of pH; approximately a 30% increase in H^+), and it is estimated that it will drop by a further 0.3 to 0.5 units (more than doubling ocean H^+ concentrations) by 2100 as the oceans absorb more anthropogenic CO_2 .

Oxygen depletion

The amount of oxygen dissolved in the oceans may decline, with adverse consequences for ocean life.

Sea level rise



IPCC (2007a:5) reported that since 1961, global average sea level had risen at an average rate of 1.8 [1.3 to 2.3] mm/yr. Between 1993 and 2003, the rate increased above the previous period to 3.1 [2.4 to 3.8] mm/yr. IPCC (2007a) were uncertain whether the increase in rate from 1993 to 2003 was due to natural variations in sea level over the time period, or whether it reflected an increase in the underlying long-term trend.

IPCC (2007a:13, 14) projected sea level rise to the end of the 21st century using the SRES emission scenarios. Across the six SRES marker scenarios, sea level was projected to rise by 18 to 59 cm (7.1 to 23.2 inches). This projection was for the time period 2090-2099, with the increase in level relative to average sea levels over the 1980-1999 period. Due to a lack of scientific understanding, this sea level rise estimate does not include all of the possible contributions of ice sheets.

Temperature rise

From 1961 to 2003, the global ocean temperature has risen by 0.10 °C from the surface to a depth of 700 m. There is variability both year-to-year and over longer time scales, with global ocean heat content observations showing high rates of warming for 1991 to 2003, but some cooling from 2003 to 2007. The temperature of the Antarctic Southern Ocean rose by 0.17 °C (0.31 °F) between the 1950s and the 1980s, nearly twice the rate for the world's oceans as a whole. As well as having effects on ecosystems (e.g. by melting sea ice, affecting algae that grow on its underside), warming reduces the ocean's ability to absorb CO₂.

Social systems

Food supply

Climate change will impact agriculture and food production around the world due to: the effects of elevated CO₂ in the atmosphere, higher temperatures, altered precipitation and transpiration regimes, increased frequency of extreme events, and modified weed, pest, and pathogen pressure (Easterling *et al.*, 2007:282). In general, low-latitude areas are at most risk of having decreased crop yields (Schneider *et al.*, 2007:790). With low to medium confidence, Schneider *et al.* (2007:787) concluded that for about a 1 to 3°C global mean temperature increase (by 2100, relative to the 1990-2000 average level) there would be productivity decreases for some cereals in low latitudes, and productivity increases in high latitudes. With medium confidence, global production potential was predicted to:

- increase up to around 3°C,
- very likely decrease above about 3 to 4°C.

Most of the studies on global agriculture assessed by Schneider *et al.* (2007:790) had not incorporated a number of critical factors, including changes in extreme events, or the spread of pests and diseases. Studies had also not considered the development of specific practices or technologies to aid adaptation.

Health

Human beings are exposed to climate change through changing weather patterns (temperature, precipitation, sea-level rise and more frequent extreme events) and indirectly through changes in water, air and food quality and changes in ecosystems, agriculture, industry and settlements and the economy (Confalonieri *et al.*, 2007:393). According to a literature assessment by Confalonieri *et al.* (2007:393), the effects of climate change to date have been small, but are projected to progressively increase in all countries and regions.

With high confidence, Confalonieri *et al.* (2007:393) concluded that climate change had altered the seasonal distribution of some allergenic pollen species. With medium confidence, they concluded that climate change had:

- altered the distribution of some infectious disease vectors
- increased heatwave-related deaths

With high confidence, IPCC (2007d:48) projected that:

- the health status of millions of people would be affected through, for example, increases in malnutrition; increased deaths, diseases and injury due to extreme weather events; increased burden of diarrhoeal diseases; increased frequency of cardio-respiratory diseases due to high concentrations of ground-level ozone in urban areas related to climate change; and altered spatial distribution of some infectious diseases.
- climate change would bring some benefits in temperate areas, such as fewer deaths from cold exposure, and some mixed effects such as changes in range and transmission potential of malaria in Africa. Overall, IPCC (2007d:48) expected that benefits would be outweighed by negative health effects of rising temperatures, especially in developing countries.

With very high confidence, Confalonieri *et al.* (2007:393) concluded that economic development was an important component of possible adaptation to climate change. Economic growth on its own, however, was not judged to be sufficient to insulate the world's population from disease and injury due to climate change. The manner in which economic growth occurs was judged to be important, along with how the benefits of growth are distributed in society. Examples of other important factors in determining the health of populations were listed as: education, health care, and public-health infrastructure.

Specific health impacts

Malnutrition

With high confidence, Confalonieri *et al.* (2007) projected that malnutrition would increase due to climate change. This link is associated with climate variability and change (Confalonieri *et al.*, 2007). Drought reduces variety in diets and reduces overall consumption. This can lead to micronutrient deficiencies.

The World Health Organization (WHO) (referred to by Confalonieri *et al.*, 2007) conducted a regional and global assessment to quantify the amount of premature morbidity and mortality due to a range of factors, including climate change. Projections were made over future climate change impacts. Limited adjustments for adaptation were included in the estimates based on these projections. Projected relative risks attributable to climate change in 2030 varied by health outcome and region. Risks were largely negative, with most of the projected disease burden due to increases in diarrhoeal disease

and malnutrition. These increases were primarily in low-income populations already experiencing a large burden of disease.

Extreme events

With high confidence, Confalonieri *et al.* (2007) projected that climate change would increase the number of people suffering from death, disease and injury from heatwaves, floods, storms, fires and droughts.

Floods and weather disasters

Floods are low-probability, high-impact events that can overwhelm physical infrastructure and human communities (Confalonieri *et al.*, 2007). Major storm and flood disasters have occurred in the last two decades.

The impacts of weather disasters is considerable and unequally distributed. For example, natural disasters have been shown to result in increased domestic violence against - and post-traumatic stress disorders in – women. In terms of deaths and populations affected, floods and tropical cyclones have the greatest impact in South Asia and Latin America. Vulnerability to weather disasters depends on the attributes of the person at risk, including where they live and their age, as well as other social and environmental factors. High-density populations in low-lying coastal regions experience a high health burden from weather disasters.

Heatwaves

Hot days, hot nights and heatwaves have become more frequent (Confalonieri *et al.*, 2007). Heatwaves are associated with marked short-term increases in mortality. For example, in August 2003, a heatwave in Europe resulted in excess mortality in the range of 35,000 total deaths.

Heat-related morbidity and mortality is projected to increase (Confalonieri *et al.*, 2007). The health burden could be relatively small for moderate heatwaves in temperate regions, because deaths occur primarily in susceptible persons.

Drought

The effects of drought on health include deaths, malnutrition, infectious diseases and respiratory diseases (Confalonieri *et al.*, 2007). Countries within the "Meningitis Belt" in semi-arid sub-Saharan Africa experience the highest endemicity and epidemic frequency of meningococcal meningitis in Africa, although other areas in the Rift Valley, the Great Lakes, and southern Africa are also affected (Confalonieri *et al.*, 2007). The spatial distribution, intensity, and seasonality of meningococcal (epidemic) meningitis appear to be strongly linked to climate and environmental factors, particularly drought. The cause of this link is not fully understood.

Fires

In some regions, changes in temperature and precipitation are projected to increase the frequency and severity of fire events (Confalonieri *et al.*, 2007). Forest and bush fires cause burns, damage from smoke inhalation and other injuries.

Infectious disease vectors

With high confidence, Confalonieri *et al.* (2007) projected that climate change would continue to change the range of some infectious disease vectors. Vector-borne diseases (VBD) are infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies, and blackflies (Confalonieri *et al.*, 2007). There is some evidence of climate-change-related shifts in the distribution of tick vectors of disease, of some (non-malarial) mosquito vectors in Europe and North America. Climate change has also been implicated in changes in the breeding and migration dates of several bird species. Several species of wild bird can act as carriers of human pathogens as well as of vectors of infectious agents.

Dengue

It is possible^d that climate change will increase the number of people at risk of dengue (Confalonieri *et al.*, 2007). Based on the expert judgement of Confalonieri *et al.* (2007), this projection had about a two-in-ten chance of being correct. Dengue is the world's most important vector-borne viral disease (Confalonieri *et al.*, 2007). Several studies have reported associations between dengue and climate, however, these associations are not entirely consistent.

Malaria

The spatial distribution, intensity of transmission, and seasonality of malaria is influenced by climate in Sub-saharan Africa (Confalonieri *et al.*, 2007). Rainfall can be a limiting factor for mosquito populations and there is some evidence of reductions in transmission associated with decadal decreases in rainfall. The effects of observed climate change on the geographical distribution of malaria and its transmission intensity in highland regions remains controversial. There is no clear evidence that malaria has been affected by climate change in South America or in continental regions of the Russian Federation. There is still much uncertainty about the potential impact of climate change on malaria at local and global scales.

A paper by researchers from the University of Oxford and the University of Florida published in *Nature* in May 2010 concluded that claims that a warming climate has led to more widespread disease and death due to malaria are largely at odds with the evidence, and that "*predictions of an intensification of malaria in a warmer world, based on extrapolated empirical relationships or biological mechanisms, must be set against a context of a century of warming that has seen marked global declines in the disease and a*

substantial weakening of the global correlation between malaria endemicity and climate."

Other infectious diseases

There is good evidence that diseases transmitted by rodents sometimes increase during heavy rainfall and flooding because of altered patterns of human-pathogen-rodent contact (Confalonieri *et al.*, 2007).

Projections

With very high confidence, Confalonieri *et al.* (2007) concluded that climate change would have mixed effects on malaria. Malaria is a complex disease to model and all of the published models assessed by Confalonieri *et al.* (2007) had limited parameterization of some key factors. Parameterization is used in climate models because the resolution of models is insufficient to resolve some physical processes (Randall *et al.*, 2007). Given this limitation, models assessed by Confalonieri *et al.* (2007) projected that, particularly in Africa, climate change would be associated with geographical expansions of the areas suitable for *Plasmodium falciparum* malaria in some regions, and contractions in other regions. Projections also suggested that some regions would experience a longer season of transmission. Projections suggested expansions in vector species that carry dengue for parts of Australia and New Zealand.

Diarrhoeal diseases

With medium confidence, Confalonieri *et al.* (2007) concluded that climate change would increase the burden of diarrhoeal diseases. Childhood mortality due to diarrhoea in low-income countries, especially in Sub-Saharan Africa, remains high (Confalonieri *et al.*, 2007). This is despite improvements in care. Several studies have shown that transmission of enteric pathogens is higher during the rainy season. Some studies have found that higher temperature was strongly associated with increased episodes of diarrhoeal disease in adults and children in Peru. The WHO study, referred to earlier, projected that climate change would increase the burden of diarrhoeal diseases in low-income regions by approximately 2 to 5% in 2020 (Confalonieri *et al.*, 2007).

Ground-level ozone

With high confidence, Confalonieri *et al.* (2007) projected that climate change would increase cardio-respiratory morbidity and mortality associated with ground-level ozone. Ground-level ozone is both naturally occurring and is the primary constituent of urban smog (Confalonieri *et al.*, 2007). Ozone in smog is formed through chemical reactions involving nitrogen oxides and other compounds. The reaction is a photochemical reaction, meaning that it involves electromagnetic radiation, and occurs in the presence of bright sunshine and high temperatures. Exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive

pulmonary disease, asthma, allergic rhinitis and other respiratory diseases, and with premature mortality.

Background levels of ground-level ozone have risen since pre-industrial times because of increasing emissions of methane, carbon monoxide and nitrogen oxides (Confalonieri *et al.*, 2007). This trend is expected to continue into the mid-21st century.

Cold-waves

It is expected that^b climate change will bring some health benefits (Confalonieri *et al.*, 2007). It is expected that these benefits will be outweighed by negative climate change effects.

Cold-waves continue to be a problem in northern latitudes, where very low temperatures can be reached in a few hours and extend over long periods (Confalonieri *et al.*, 2007). Reductions in cold-deaths due to climate change are projected to be greater than increases in heat-related deaths in the UK (Confalonieri *et al.*, 2007).

Water resources

In a literature assessment, Kundzewicz *et al.*. (2007:175) concluded, with high confidence, that:

- the negative impacts of climate change on freshwater systems outweigh the benefits. All of the regions assessed in the IPCC Fourth Assessment Report (Africa, Asia, Australia and New Zealand, Europe, Latin America, North America, Polar regions (Arctic and Antarctic), and small islands) showed an overall net negative impact of climate change on water resources and freshwater ecosystems.
- Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater. With very high confidence, it was judged that many of these areas, e.g., the Mediterranean basin, western USA, southern Africa, and north-eastern Brazil, would suffer a decrease in water resources due to climate change.

Migration and conflict

An argument can be made that rising ethnic conflicts may be linked to competition over natural resources that are increasingly scarce as a result of climate change (Wilbanks *et al.*, 2007:365). According to a literature assessment by Wilbanks *et al.*. (2007:365), other factors need to be taken into account. It was suggested that major environmentally influenced conflicts in Africa have more to do with the relative abundance of resources, e.g., oil and diamonds, than with resource scarcity. On this basis, Wilbanks *et al.*. (2007:365) suggested that predictions of future conflicts due climate change should be viewed with caution.

With high confidence, Schneider *et al.* (2007:787) predicted that stresses such as increased drought, water shortages, and riverine and coastal flooding would affect many local and regional populations. With medium confidence, it was predicted that these stresses would lead, in some cases, to relocation within or between countries. This might have the effect of exacerbating conflicts, and possibly impose migration pressures.

Zhang *et al* also concluded that climate change drives conflict.

Aggregate impacts

Aggregating impacts adds up the total impact of climate change across sectors and/or regions (IPCC, 2007d:76). The impacts of climate change across world population will not be distributed evenly (Smith *et al.*, 2001:957). IPCC (2007b:17) found that for increases in global mean temperature of less than 1-3 °C above 1990 levels, some impacts were projected to produce benefits in some places and sectors, and produce costs in other places and sectors. For some low-latitude and polar regions, net costs were projected for small increases in temperature. According to IPCC (2007b:17), a temperature increase of greater than about 2-3 °C would very likely result in all regions either experiencing reductions in net benefits or increases in net costs.

Regions

Some regions are likely to be especially affected by climate change (IPCC, 2007d:9):

- The Arctic, because of high rates of projected warming.
- Africa, especially in the sub-Saharan region. This is due to the continent's low capacity to adapt to climate change and projected impacts.
- Small islands, due to high exposure of population and infrastructure at risk to sea-level rise and increased storm surge.
- Asian megadeltas, due to large populations and high exposure to sea-level rise, storm surge and river flooding.

Within other areas, some people are particularly at risk, such as the poor, young children and the elderly.

Biological systems

With very high confidence, Schneider *et al.* (2007:792) concluded that regional temperature trends were already affecting species and ecosystems around the world. In a literature assessment, Rosenzweig *et al.* (2007:81) concluded that over the last three decades, human-induced warming had likely had a discernable influence on many physical and biological systems.

Schneider *et al.* (2007:792) concluded, with high confidence, that climate change would result in the extinction of many species and a reduction in the diversity of ecosystems.

- **Terrestrial ecosystems and biodiversity:** With a warming of 3°C, relative to 1990 levels, it is likely that global terrestrial vegetation would become a net source of carbon (Schneider *et al.*, 2007:792). With high confidence, Schneider *et al.* (2007:788) concluded that a global mean temperature increase of around 4°C (above the 1990-2000 level) by 2100 would lead to major extinctions around the globe.
- **Marine ecosystems and biodiversity:** With very high confidence, Schneider *et al.* (2007:792) concluded that a warming of 2°C above 1990 levels would result in mass mortality of coral reefs globally.
- **Freshwater ecosystems:** Above about a 4°C increase in global mean temperature by 2100 (relative to 1990-2000), Schneider *et al.* (2007:789) concluded, with high confidence, that many freshwater species would become extinct.

Abrupt or irreversible changes

Abrupt climate change

Abrupt climate change is defined as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems (CCSP, 2008a). There is the possibility of a rapid change in glaciers, ice sheets, and hence sea level. Predictions of such a change are highly uncertain due to a lack of scientific understanding. Modeling of the processes associated with a rapid ice sheet and glacier change could potentially increase future projections of sea level rise.

The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the Earth's climate system, characterized by a northward flow of warm, salty water in the upper layers of the Atlantic and a southward flow of colder water in the deep Atlantic (CCSP, 2008b, p. 5). Potential impacts associated with MOC changes include reduced warming or (in the case of abrupt change) absolute cooling of northern high-latitude areas near Greenland and north-western Europe, an increased warming of Southern Hemisphere high-latitudes, tropical drying, as well as changes to marine ecosystems, terrestrial vegetation, oceanic CO₂ uptake, oceanic oxygen concentrations, and shifts in fisheries (Schneider *et al.*, 2007). According to a assessment by the US Climate Change Science Program (CCSP, 2008b, p. 5), it is very likely that the strength of the AMOC will decrease over the course of the 21st century. Warming is still expected to occur over most of the European region downstream of the North Atlantic Current in response to increasing greenhouse gases, as well as over North America. Although it is very unlikely that the AMOC will collapse in the 21st century, the potential consequences of such a collapse could be severe.

Irreversibilities

An irreversible change is one where that change, once set in motion, cannot be reversed, at least over some specified timescale, e.g., centuries to millennia (Goldemberg *et al.*, 1996, p. 22). Climate change is likely to lead to some irreversible impacts (IPCC, 2007d). One example of a potentially irreversible impact of climate change is damage to ecosystems.

Footnotes

The IPCC report that is referred to in this specific and quantitative language to describe uncertainty (Ahmad *et al.*, 2001). This language is intended to provide an indication of the level of confidence that IPCC authors have about a particular finding. The qualitative language used to describe uncertainty has a quantitative scale associated with it. The quantitative values for qualitative terms are intended to ensure that confidence levels are interpreted correctly. This is because qualitative statements, e.g., using the word "likely," can be interpreted differently in quantitative terms (Moss and Schneider, 2000, p. 44).

Quantitative values for confidence statements made in the IPCC Fourth Assessment Report are listed below (IPCC, 2007). These quantitative values are subjective probabilities that reflect the expert judgement of IPCC authors:

- ^a Very high confidence: At least 9 out of 10 chance of being correct
- ^b High confidence: About 8 out of 10 chance
- ^c Medium confidence: About 5 out of 10 chance
- ^d Low confidence: About 2 out of 10 chance
- ^e Very low confidence: Less than a 1 out of 10 chance

Chapter- 7

Global Climate Change

Climate change is a change in the statistical distribution of weather over periods of time that range from decades to millions of years. It can be a change in the average weather or a change in the distribution of weather events around an average (for example, greater or fewer extreme weather events). Climate change may be limited to a specific region, or may occur across the whole Earth.

In recent usage, especially in the context of environmental policy, climate change usually refers to changes in modern climate. It may be qualified as anthropogenic climate change, more generally known as "global warming" or "anthropogenic global warming" (AGW).

Terminology

The most general definition of *climate change* is a change in the statistical properties of the climate system when considered over periods of decades or longer, regardless of cause. Accordingly, fluctuations on periods shorter than a few decades, such as El Niño, do not represent climate change.

The term sometimes is used to refer specifically to climate change caused by human activity; for example, the United Nations Framework Convention on Climate Change defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." In the latter sense climate change is synonymous with global warming.

Causes

Factors that can shape climate are climate forcings. These include such processes as variations in solar radiation, deviations in the Earth's orbit, mountain-building and continental drift, and changes in greenhouse gas concentrations. There are a variety of climate change feedbacks that can either amplify or diminish the initial forcing. Some parts of the climate system, such as the oceans and ice caps, respond slowly in reaction to climate forcing because of their large mass. Therefore, the climate system can take centuries or longer to fully respond to new external forcings.

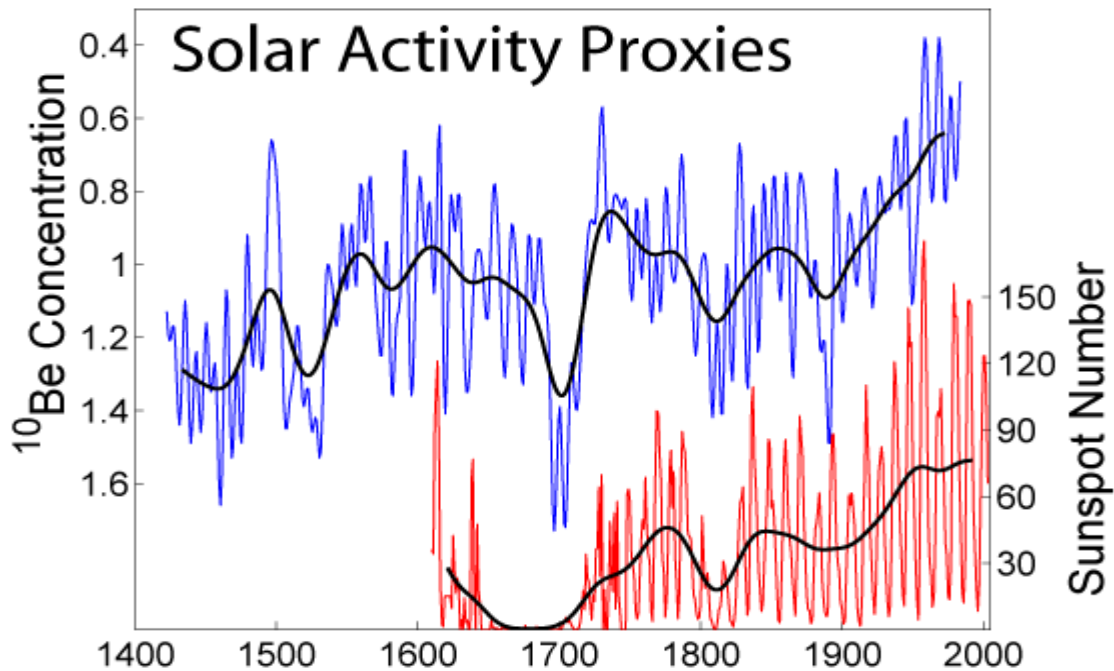
Plate tectonics

Over the course of millions of years, the motion of tectonic plates reconfigures global land and ocean areas and generates topography. This can affect both global and local patterns of climate and atmosphere-ocean circulation.

The position of the continents determines the geometry of the oceans and therefore influences patterns of ocean circulation. The locations of the seas are important in controlling the transfer of heat and moisture across the globe, and therefore, in determining global climate. A recent example of tectonic control on ocean circulation is the formation of the Isthmus of Panama about 5 million years ago, which shut off direct mixing between the Atlantic and Pacific Oceans. This strongly affected the ocean dynamics of what is now the Gulf Stream and may have led to Northern Hemisphere ice cover. During the Carboniferous period, about 300 to 360 million years ago, plate tectonics may have triggered large-scale storage of carbon and increased glaciation. Geologic evidence points to a "megamonsoonal" circulation pattern during the time of the supercontinent Pangaea, and climate modeling suggests that the existence of the supercontinent was conducive to the establishment of monsoons.

The size of continents is also important. Because of the stabilizing effect of the oceans on temperature, yearly temperature variations are generally lower in coastal areas than they are inland. A larger supercontinent will therefore have more area in which climate is strongly seasonal than will several smaller continents or islands.

Solar output



Variations in solar activity during the last several centuries based on observations of sunspots and beryllium isotopes.

The sun is the predominant source for energy input to the Earth. Both long- and short-term variations in solar intensity are known to affect global climate.

Three to four billion years ago the sun emitted only 70% as much power as it does today. If the atmospheric composition had been the same as today, liquid water should not have existed on Earth. However, there is evidence for the presence of water on the early Earth, in the Hadean and Archean eons, leading to what is known as the faint young sun paradox. Hypothesized solutions to this paradox include a vastly different atmosphere, with much higher concentrations of greenhouse gases than currently exist. Over the following approximately 4 billion years, the energy output of the sun increased and atmospheric composition changed, with the oxygenation of the atmosphere around 2.4 billion years ago being the most notable alteration. These changes in luminosity, and the sun's ultimate death as it becomes a red giant and then a white dwarf, will have large effects on climate, with the red giant phase possibly ending life on Earth.

Solar output also varies on shorter time scales, including the 11-year solar cycle and longer-term modulations. Solar intensity variations are considered to have been influential in triggering the Little Ice Age and some of the warming observed from 1900 to 1950. The cyclical nature of the sun's energy output is not yet fully understood; it differs from the very slow change that is happening within the sun as it ages and evolves. While most research indicates solar variability has induced a small cooling effect from 1750 to the present, a few studies point toward solar radiation increases from cyclical sunspot activity affecting global warming.

Orbital variations

Slight variations in Earth's orbit lead to changes in the seasonal distribution of sunlight reaching the Earth's surface and how it is distributed across the globe. There is very little change to the area-averaged annually averaged sunshine; but there can be strong changes in the geographical and seasonal distribution. The three types of orbital variations are variations in Earth's eccentricity, changes in the tilt angle of Earth's axis of rotation, and precession of Earth's axis. Combined together, these produce Milankovitch cycles which have a large impact on climate and are notable for their correlation to glacial and interglacial periods, their correlation with the advance and retreat of the Sahara and for their appearance in the stratigraphic record.

Volcanism

Volcanism is a process of conveying material from the crust and mantle of the Earth to its surface. Volcanic eruptions, geysers, and hot springs, are examples of volcanic processes which release gases and/or particulates into the atmosphere.

Eruptions large enough to affect climate occur on average several times per century, and cause cooling (by partially blocking the transmission of solar radiation to the Earth's surface) for a period of a few years. The eruption of Mount Pinatubo in 1991, the second largest terrestrial eruption of the 20th century (after the 1912 eruption of Novarupta)

affected the climate substantially. Global temperatures decreased by about 0.5 °C (0.9 °F). The eruption of Mount Tambora in 1815 caused the Year Without a Summer. Much larger eruptions, known as large igneous provinces, occur only a few times every hundred million years, but may cause global warming and mass extinctions.

Volcanoes are also part of the extended carbon cycle. Over very long (geological) time periods, they release carbon dioxide from the Earth's crust and mantle, counteracting the uptake by sedimentary rocks and other geological carbon dioxide sinks. According to the US Geological Survey, however, estimates are that human activities generate more than 130 times the amount of carbon dioxide emitted by volcanoes.

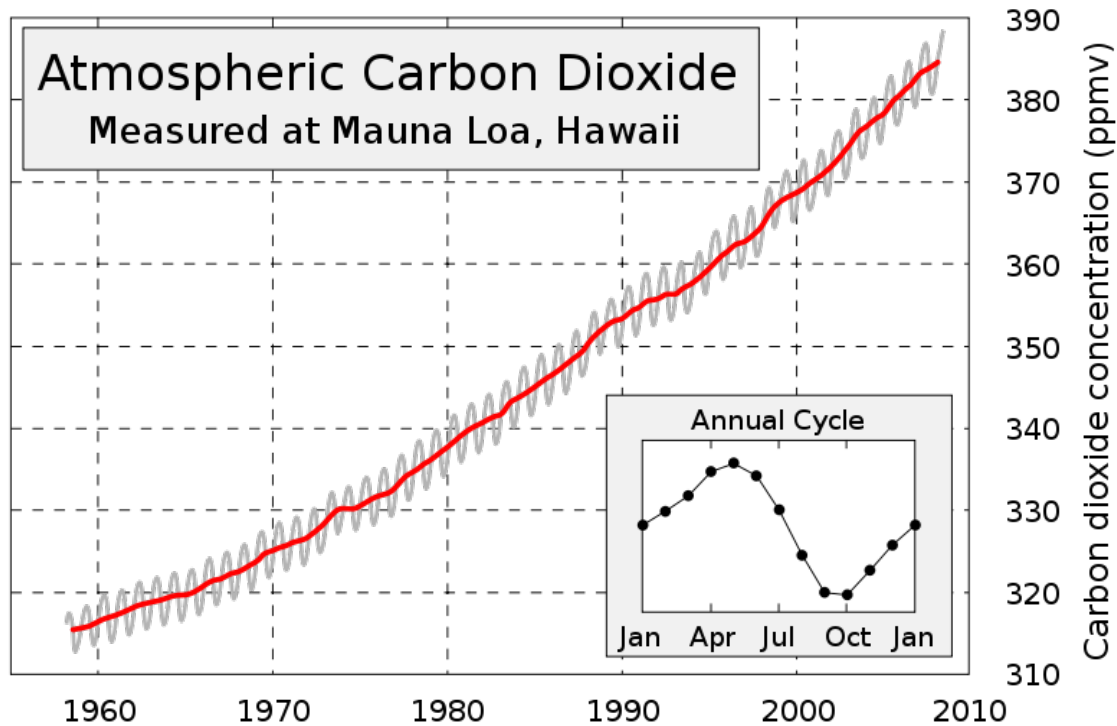
Ocean variability



A schematic of modern thermohaline circulation

The ocean is a fundamental part of the climate system. Short-term fluctuations (years to a few decades) such as the El Niño–Southern Oscillation, the Pacific decadal oscillation, the North Atlantic oscillation, and the Arctic oscillation, represent climate variability rather than climate change. On longer time scales, alterations to ocean processes such as thermohaline circulation play a key role in redistributing heat by carrying out a very slow and extremely deep movement of water, and the long-term redistribution of heat in the world's oceans.

Human influences



Increase in Atmospheric CO₂ Levels

Anthropogenic factors are human activities that change the environment. In some cases the chain of causality of human influence on the climate is direct and unambiguous (for example, the effects of irrigation on local humidity), while in other instances it is less clear. Various hypotheses for human-induced climate change have been argued for many years. Presently the scientific consensus on climate change is that human activity is very likely the cause for the rapid increase in global average temperatures over the past several decades. Consequently, the debate has largely shifted onto ways to reduce further human impact and to find ways to adapt to change that has already occurred.

Of most concern in these anthropogenic factors is the increase in CO₂ levels due to emissions from fossil fuel combustion, followed by aerosols (particulate matter in the atmosphere) and cement manufacture. Other factors, including land use, ozone depletion, animal agriculture and deforestation, are also of concern in the roles they play - both separately and in conjunction with other factors - in affecting climate, microclimate, and measures of climate variables.

Physical evidence for climatic change

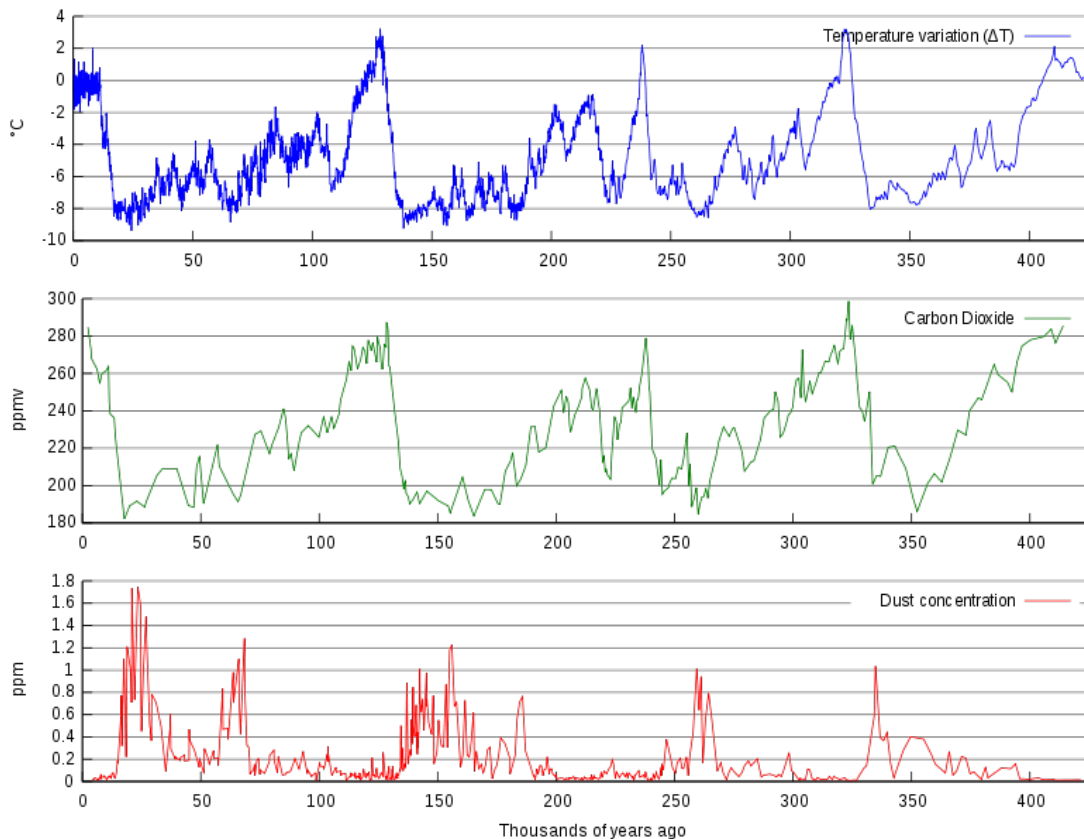
Evidence for climatic change is taken from a variety of sources that can be used to reconstruct past climates. Reasonably complete global records of surface temperature are available beginning from the mid-late 1800s. For earlier periods, most of the evidence is indirect—climatic changes are inferred from changes in proxies, indicators that reflect

climate, such as vegetation, ice cores, dendrochronology, sea level change, and glacial geology.

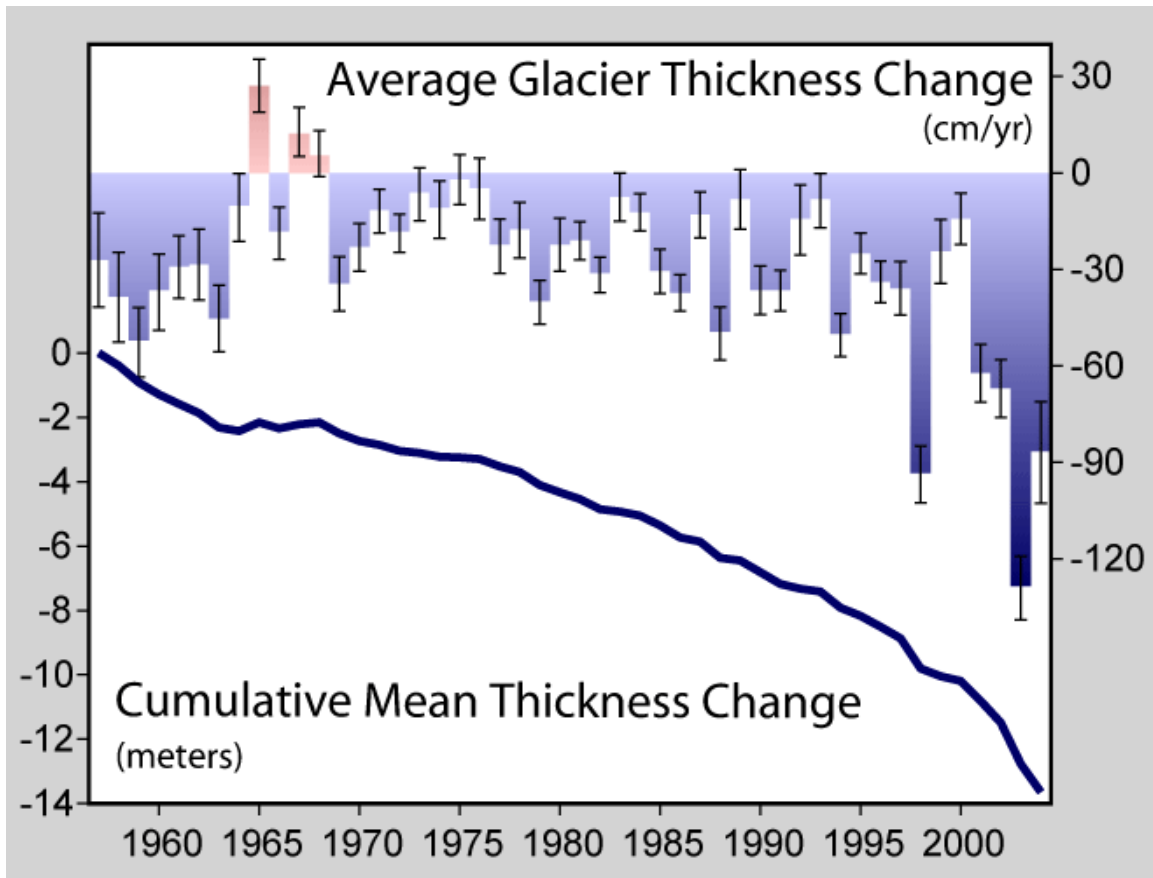
Historical and archaeological evidence

Climate change in the recent past may be detected by corresponding changes in settlement and agricultural patterns. Archaeological evidence, oral history and historical documents can offer insights into past changes in the climate. Climate change effects have been linked to the collapse of various civilisations.

Glaciers



Variations in CO₂, temperature and dust from the Vostok ice core over the last 450,000 years



Decline in thickness of glaciers worldwide

Glaciers are considered among the most sensitive indicators of climate change, advancing when climate cools and retreating when climate warms. Glaciers grow and shrink, both contributing to natural variability and amplifying externally forced changes. A world glacier inventory has been compiled since the 1970s, initially based mainly on aerial photographs and maps but now relying more on satellites. This compilation tracks more than 100,000 glaciers covering a total area of approximately 240,000 km², and preliminary estimates indicate that the remaining ice cover is around 445,000 km². The World Glacier Monitoring Service collects data annually on glacier retreat and glacier mass balance. From this data, glaciers worldwide have been found to be shrinking significantly, with strong glacier retreats in the 1940s, stable or growing conditions during the 1920s and 1970s, and again retreating from the mid 1980s to present.

The most significant climate processes since the middle to late Pliocene (approximately 3 million years ago) are the glacial and interglacial cycles. The present interglacial period (the Holocene) has lasted about 11,700 years. Shaped by orbital variations, responses such as the rise and fall of continental ice sheets and significant sea-level changes helped create the climate. Other changes, including Heinrich events, Dansgaard–Oeschger events and the Younger Dryas, however, illustrate how glacial variations may also influence climate without the orbital forcing.

Glaciers leave behind moraines that contain a wealth of material—including organic matter, quartz, and potassium that may be dated—recording the periods in which a glacier advanced and retreated. Similarly, by tephrochronological techniques, the lack of glacier cover can be identified by the presence of soil or volcanic tephra horizons whose date of deposit may also be ascertained.

Vegetation

A change in the type, distribution and coverage of vegetation may occur given a change in the climate; this much is obvious. In any given scenario, a mild change in climate may result in increased precipitation and warmth, resulting in improved plant growth and the subsequent sequestration of airborne CO₂. Larger, faster or more radical changes, however, may well result in vegetation stress, rapid plant loss and desertification in certain circumstances.

Ice cores

Analysis of ice in a core drilled from a ice sheet such as the Antarctic ice sheet, can be used to show a link between temperature and global sea level variations. The air trapped in bubbles in the ice can also reveal the CO₂ variations of the atmosphere from the distant past, well before modern environmental influences. The study of these ice cores has been a significant indicator of the changes in CO₂ over many millennia, and continues to provide valuable information about the differences between ancient and modern atmospheric conditions.

Dendroclimatology

Dendroclimatology is the analysis of tree ring growth patterns to determine past climate variations. Wide and thick rings indicate a fertile, well-watered growing period, whilst thin, narrow rings indicate a time of lower rainfall and less-than-ideal growing conditions.

Pollen analysis

Palynology is the study of contemporary and fossil palynomorphs, including pollen. Palynology is used to infer the geographical distribution of plant species, which vary under different climate conditions. Different groups of plants have pollen with distinctive shapes and surface textures, and since the outer surface of pollen is composed of a very resilient material, they resist decay. Changes in the type of pollen found in different layers of sediment in lakes, bogs, or river deltas indicate changes in plant communities. These changes are often a sign of a changing climate. As an example, palynological studies have been used to track changing vegetation patterns throughout the Quaternary glaciations and especially since the last glacial maximum.

Insects

Remains of beetles are common in freshwater and land sediments. Different species of beetles tend to be found under different climatic conditions. Given the extensive lineage of beetles whose genetic makeup has not altered significantly over the millennia, knowledge of the present climatic range of the different species, and the age of the sediments in which remains are found, past climatic conditions may be inferred.

Sea level change

Global sea level change for much of the last century has generally been estimated using tide gauge measurements collated over long periods of time to give a long-term average. More recently, altimeter measurements — in combination with accurately determined satellite orbits — have provided an improved measurement of global sea level change. To measure sea levels prior to instrumental measurements, scientists have dated coral reefs that grow near the surface of the ocean, coastal sediments, marine terraces, ooids in limestones, and nearshore archaeological remains. The predominant dating methods used are uranium series and radiocarbon, with cosmogenic radionuclides being sometimes used to date terraces that have experienced relative sea level fall.