THE ICE AGE: What & Why

Donald Bogard, May, 2018

Today, when many are concerned about the Earth possibly over-heating through greenhouse warming, it is worthwhile to look into the not very distant past when the Earth over-cooled. Most people have heard of the Ice Age but probably know very little about it. Some may remember climate scientists in the 1970s expressing concern that Earth might be entering a new ice age, because of growing evidence that Earth was cooling (in spite of growing atmospheric carbon dioxide, or CO2). What was the ice age, why did it occur, and is it now in our past, or also in our future? This summary addresses these questions. Although there are multiple viewpoints for some Ice Age characteristics, it is the major opinion views that are presented here.

The What.

The ice age was a period of time when massive sea ice and glacial land ice formed over the far northern hemisphere and moved southward into the United States and northern Europe (Figure 1). The ice coverage came in multiple cycles called glacials, each about 100,000 years long, and separated by warm periods of about 10,000 years, called interglacials. We are presently in an interglacial called the Holocene, and it is about 10,000 years old. (The Earth experienced a few much earlier ice ages, but here we consider only the most recent one.) Earth slipped gradually into this ice age, and its exact beginning is not precisely defined (see below). However, data acquired from Antarctic ice cores (described below) show that these glacial-interglacial cycles go back at least 800,000 years and likely much further. Each cycle was similar, although not identical. The last interglacial (~130 to 120 thousand years ago) reached temperatures a few degrees warmer than today and maintained global temperatures similar to or higher than current global temperatures for up to 10,000 years. However, this previous interglacial had atmospheric CO2 concentrations levels (~280 ppm) only 69% as high as todays. The extensive ice caps present today on Antarctica and Greenland, which are remnants from the last glaciation, were smaller 120 thousand years ago than they are today, and as a result Earth's sea level was about 20 feet higher. A longer time of higher temperature for the past interglacial compared to our Holocene probably caused the more extensive ice melting and sea rise.

About 120 thousand years ago, both temperature and atmospheric CO2 began to substantially decrease, with falling temperature leading the CO2. Winter snow that fell in the far northern hemisphere began to survive summer melting and accumulated. As snow depth deepened, overlying pressure turned it to ice, and this ice cover gradually extended southward, growing thicker. In North America, two of the major ice spreading centers lay on either side of northern Hudson Bay, areas today that possess mild summers supporting green plants. Temperature did not decrease uniformly, but following an initial steep, major decrease, subsequently moved erratically downward and even partially rebounded for short periods. Falling CO2 concentrations and sea level approximately correlated with falling temperatures. The glacial ice coverage sometimes reached two miles thick, a thickness comparable to the inner ice caps on Antarctica and Greenland today. At the

time of maximum ice coverage and lowest temperature, glacial ice covered about 27% of Earth's current land surface and moved well south of the Great Lakes. During some glacial cycles ice advanced as far south as the Ohio River, northern Missouri, and beyond New York City. Ice also covered northern Germany, Poland, north-west Russia, and northern Japan. Because the southern hemisphere contains much less land, glacial ice there was far less extensive, but did occur in far southern South America (Patagonia) and New Zealand.

In addition to changes described above, additional major changes occurred on Earth's surface during times of major glaciation. Huge amounts of ocean water were converted to ice on land, and the global sea level dropped by about 120 meters (about 400 feet). About three percent of the volume of the world's oceans was moved into glacial land ice. The quantity of land ice was equivalent to covering the lower 48 United States to a depth of over 5 kilometers, or the state of Texas to a depth of about 60 kilometers. Lowered sea level exposed large areas of continental shelf, which are edges of continents covered by shallow ocean today. In the far northern hemisphere, these exposed continental shelves were also covered by glacial ice, including areas between Britain and Europe, the Barents Sea, upper east coast of North America, etc. Glaciers in northern or high mountains greatly expanded. Glaciers in the northern Rockies moved into lower levels to the east and west and eventually joined with glaciers spreading from the Hudson Bay region. Himalayan glaciers expanded northward into southern China. Figure 1 depicts the approximate spread of permanent northern hemisphere ice on both land and sea. It is difficult to show on such graphics exposure of continental shelves, then covered by land ice, and shrinkage of some sea basins, then covered by floating ice. Even unglaciated seas, such as the Mediterranean, became much smaller. More land ice formed in North America than in Euro-Asia, although some far north regions such as northern Alaska remained largely ice-free.

Another characteristic of large moving glaciers is that they can be very efficient at eroding the surface and changing the landscape. All the Great Lakes were greatly expanded by the repeated ice age cycles of moving ice. The deepest bottom of Lake Superior (world's largest freshwater lake) lies over 200 meters (>650 feet) below sea level, which demonstrates the ability of glaciers to excavate. Meltwater from glacial melting greatly expanded the St. Lawrence River and Seaway along an ancient rift system. A few million years ago, prior to repeated glacial cycles, the Baltic Sea stretching between Scandinavia and the rest of Europe, was a large land valley near sea level. Moving glaciers excavated it to below sea level. Repeated ice advances in North America also changed the drainage patterns of some rivers (including the Ohio), as their watersheds or main channels became ice-covered. The role of Lake Winnipeg in Canada in receiving runoff from northern Montana to Minnesota was significantly expanded before and during melting of glacial coverage. Sea Ice coverage also greatly expanded. (Floating sea ice does not raise sea level.) During times of maximum glaciation, probably the Atlantic north of a line stretching from France to Iceland to southern Greenland and along the upper US coast (then farther offshore) experienced year-round sea ice (Fig. 1). Temperatures across much of the Northern Hemisphere during glacial maximums were much colder than today, and even temperatures in other parts of the world were lowered by a few degrees (more later on temperature).

Then about 20 thousand years ago, temperatures began to rapidly rise, ice rapidly melted and receded northward, and sea level rose. By about 10 thousand years ago the Earth had reached a state similar to its current one, and temperature and sea level have only varied modestly since. Few people appreciate how different the northern hemisphere environment was during past glacial cycles and how much legacy these massive glaciers leave behind.

One Why: Global Cooling.

Conditions that led to the Ice Age started about 50 million years (Myr) ago, when global temperatures began to steadily decrease. Over the past 500 Myr, global temperature was mostly slightly warmer than today's, although cooler periods occurred during previous ice ages about 300 Myr and 450

Myr ago. Over most of the past 500 Myr, atmospheric CO_2 was higher than today's (405 ppm) and typically in the range of 1,000-2,000 ppm. (During the ice age ~300 Myr ago, CO_2 levels were similar to today's.) Atmospheric CO_2 began decreasing ~100 Myr ago. Antarctica (then also located near the South Pole) was not glaciated 50 Myr ago but experienced a balmy climate. However, as temperature fell, it experienced periodic periods of partial glaciation, and ~14 Myr ago temperature fell rapidly and the Antarctic ice cap expanded. Global temperatures determined from sea bed cores taken around the world indicate that falling Antarctic temperature only slightly influenced global temperature, until ~3.5 Myr ago, when global temperature also began a noticeable decrease. About this time period, final joining of North and South America occurred, further restricting east-west movement of ocean currents. About 3 Myr ago, global and polar temperature began to show moderate cycling with periods of about 41 thousand years (Kyr). As temperature continued to fall, about 1 Myr ago the 41 Kyr temperature cycles turned into ~100 Kyr cycles and the full glaciated ice age had begun.

Although details are scarce, it is generally thought that cooling of the Earth over the past 50 Myr is associated with major changes in ocean currents driven by the breakup of a continental mass (Gondwana) in the southern hemisphere between ~150-100 Myr ago and northern migration of some of its components, Australia, Africa, India, and South America (but not Antarctica). Up until <150 Myr ago, the Atlantic Ocean did not exist, and the world's oceans were represented by a large Pacific and the Tethys Sea. Gondwana (and its northern neighbors North America and proto-Europe and Asia) efficiently blocked circum-global ocean currents in the southern hemisphere and forced such currents to mix warm equatorial ocean water into far northern and southern latitudes. The "trigger" for major cooling of Antarctica probably was the beginning of significant separation of Australia and South America from Antarctica, and the now significant Atlantic Ocean, which allows water chilled in the Arctic to flow southward on the ocean bottom and rise near Antarctica. These changes isolated Antarctica from warm oceans and created the cold circum-Antarctic ocean current to further isolate it. As glaciers grew on Antarctica, their much higher albedo reflected more sunlight back to space, further cooling the far southern hemisphere.

Decreasing atmospheric CO_2 after ~100 Myr ago probably also was a factor in Earth's cooling. CO_2 levels dropped from ~2,000 ppm 100 Myr ago, to ~300 ppm at the start of the ~100 Kyr glacial cycles. During these glacial cycles, CO_2 oscillated between ~280 ppm during interglacials and ~190 ppm at glacial maximums. Atmospheric CO_2 levels below ~200 ppm and especially below ~150 ppm can slow photosynthesis and produce existence risks to some plant types. The early Earth (>500 Myr ago) likely had quite high atmospheric CO_2 concentrations (≥5,000 ppm), and CO_2 levels have substantially declined over the geologic time that plant life on Earth has flourished. Much of this CO_2 has been converted into rock carbonates (e.g., limestone sediment). Carbonates form in shallow seas. They can precipitate inorganically, but the presence of small, living, shelled organisms greatly enhances their formation. The significant reduction in atmospheric CO_2 over geologic time was probably produced by converting atmospheric CO_2 into carbonate sediments at faster rates than crustal subduction by plate tectonics and subsequent volcanic CO_2 emission, or weathering in uplifted mountain building has converted rock back into CO_2. Thus life, which thrives on high CO_2 levels, tends to lower those CO_2 levels. Conceivably, the significant decrease in atmospheric CO_2 over the past 100 Myr was accelerated by the breakup of Gondwana Land 150-100 Myr ago into separate continents, and as a result the creation of larger areas of shallow continental shelf seas where carbonate-precipitating organisms could thrive and convert atmospheric CO_2 into limestone.

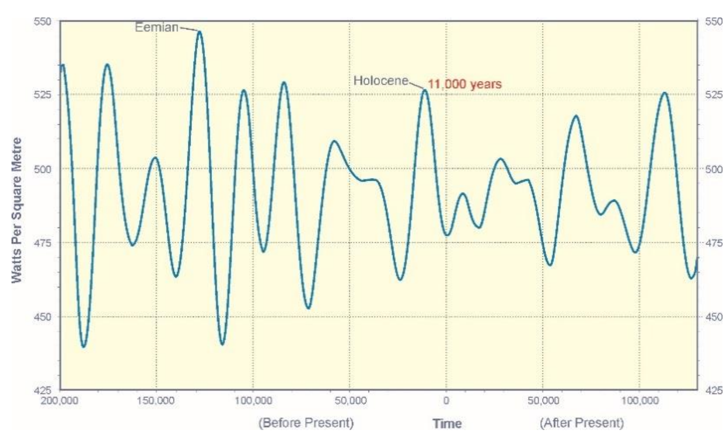
The Evidence.

Here is a very brief mention of the major types of data utilized in studying past glaciations. The positions of continents over time is derived from various kinds of field geology data, fossil life, rock types, sea levels, and isotopics. Location and movement of past glaciers are obtained from fossils and field geology data, especially erosional and depositional features specific to glaciers. Large glaciers can carve deep, steep-sided valleys and pile up huge mounds of rock debris. Temperatures and CO2 concentrations for times younger than ~800 Kyr are mostly derived from ice cores, hundreds to thousands of feet deep, drilled into the ice covering of Antarctica and Greenland. The oldest ice cores of ~800 Kyr are obtained in Antarctica. Greenland yields ice cores back to just before the last interglacial. When snow falls, accumulates, and turns to ice, it traps tiny bubbles of air which retain the relative CO2 concentrations. When snow forms from water vapor in the air, it slightly changes (isotopically fractionates) the oxygen in water, and the degree of this fractionation is proportional to ambient temperature. (Specifically, the ratio of oxygen-18 to oxygen-16 changes, and it is variations in 18O/16O at different ice depths that yields the temperature anomaly or variation.) The age of each ice core depth is determined by counting annual deposition layers (younger ice), or by age-dating layers of volcanic dust in the ice, or by measuring concentrations of radioactive materials produced in the atmosphere at relatively constant rates over time by cosmic rays (e.g. carbon-14, beryllium-10). Temperature data obtained from ice cores only describe conditions in that polar zone, and not the entire globe. Global temperature often reflects polar conditions but shows smaller variations. For older times, where ice cores are not available, and for broader coverage of Earth's surface, these same kind of isotopic data, plus certain ratios of elements (e.g., Mg/Ca) are obtained on various marine fossils in cores that are drilled into the ocean bottom. The study of paleo (pre-historic) climate data is a very large and complex field in its own right and has its own contributions and limitations.

Another Why: Insolation Changes.

Because the Earth's spin axis is tilted about 22 degrees relative to the plane of its orbit about the Sun, total sunlight (called insolation) varies considerably through the year between the northern and southern hemispheres. As the Earth yearly moves around the Sun, the two hemispheres alternate as to which is tilted sunward and receives the most insolation. This yearly variation in insolation produces the seasons, whereas the Earth spinning about its axis produces the 24-hour day-night cycle. Earth's orbit about the Sun is not round, but an oval, with the Sun located at one foci of that ellipse. Thus, when one hemisphere is tilted toward the Sun during the Earth's closest approach, that hemisphere receives more insolation than the other hemisphere, which tilts toward the Sun when it is farther away. Presently in its yearly orbit, Earth comes closest to the Sun in January, and the southern hemisphere (hereafter SH) receives more insolation year after year than the northern hemisphere (NH).

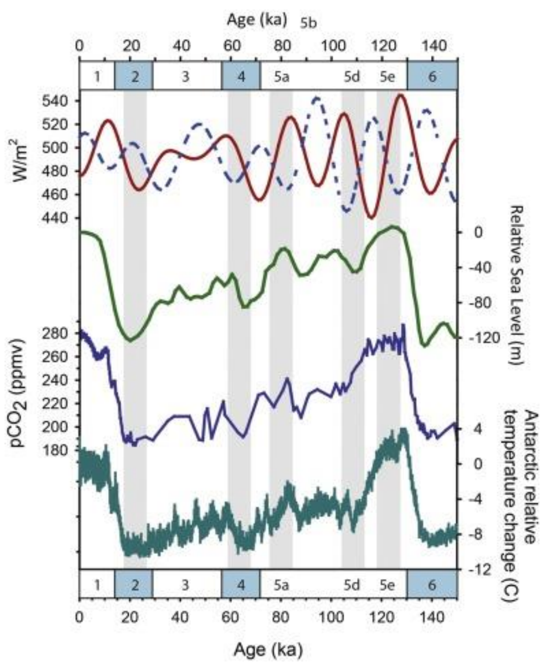
Longer term variations in insolation received by one hemisphere are produced by slow changes in the above orbital parameters. Earth's orbit shape (eccentricity) varies modestly on time scales of approximately 413, 125, and 95 Kyr. Further, both the Earth's orbit and tilt precess, or slowly vary and produce time cycles of about 41 and 23 Kyr. This precession produces long-term changes in which hemisphere receives the most insolation. In about 10 Kyr, the Earth will experience its closest approach in June, and the NH will receive more insolation than the SH. All these effects produce a very complicated pattern of insolation variation in a given hemisphere over recent geologic time. However, because Earth's orbital characteristics are very well known, the pattern of insolation for each hemisphere can be calculated rather precisely back in time, as well as into the near future. Figure 2 shows the insolation variation at summer



solstice (June 21st) and 65 degrees north latitude for the time period of 200 Kyr ago until 125 Kyr in the future.

A prominent feature of Figure 2 is the high 65N insolation at summer solstice ~130 Kyr ago, near the start of the previous interglacial (named the Eemian). Secondly, note the precipitous fall in insolation until ~115 Kyr ago. This insolation decrease was 105 watts per square meter, or ~20% of total insolation (calculated for top of atmosphere and neglecting Earth's albedo). The large insolation decrease ~120 Kyr ago closely parallels a rapid global temperature drop and falling sea level that define the beginning of the last glaciation. Intermediate amounts of rising and falling insolation occurred about every 23 Kyr thereafter, and these dips and peaks correlate with global temperature and sea level variations. Glacial ice began melting ~18 Kyr ago, and about 10 Kyr ago, a moderate insolation peak ushered in the Holocene interglacial. For the past ~8 Kyr of the Holocene, both temperature and sea level have varied only little.

Figure 3 compares for the past 140 Kyr, a) insolation at summer solstice and 60N latitude in watts per square meter, b) mean sea level determined from oxygen isotopic data on marine fossils, c) atmospheric CO2, and d) Antarctic temperature as determined from ice cores. Recognized marine isotopic stages (1-6) are also indicated at top and bottom. This is more than a complete glacial cycle, from before the Eemian interglacial to the present. A degree of correlation among all four parameters is obvious. Proxy data for sea level variations show some variations, depending on the methodology used and physical locales sampled, but this curve is representative.



Very large insolation changes, such as occurred ~120 Kyr ago, by themselves were insufficient to plunge the NH into glaciation. For comparison, the 65N insolation change between winter and summer is currently over 400 watts/sq-m. Above 65N, however, most of the insolation received occurs over only four summer months, meaning that the insolation decrease 120 Kyr ago was concentrated at times when winter snow melting occurs. (Alaska and Finland lie at 65N and can produce abundant winter snow.) Probably such large insolation drops act as a cold trigger to prevent winter snow from melting in summer at high latitudes. When snow persists through summers, its high albedo (reflectivity) prevents much of the insolation from being absorbed at the surface and further cools the surface. Such effects would be cumulative, and over periods of centuries would promote cooler temperatures and year-long snow in surrounding areas and lower latitudes. Calculations considering albedo changes indicate that spreading NH ice would substantially contribute to NH cooling and growing NH glaciation. (An older explanation, no longer favored by most, is that glaciation was initiated in warm interglacials when snowfall rates at high NH latitudes became so intense that snow-cover resisted summer melting even at the high ambient temperature. However, glacial spreading centers in northern Canada lie at relatively low latitudes, and most yearly precipitation there falls as summer rain, not winter snow.)

Once NH glaciation was well underway, other environmental changes likely enhanced cooling. Lowering sea levels would expose bare ground with higher albedo than oceans (whose albedo is quite low). Decreasing temperature might lessen plant growth and CO2 production (from soils and organic oxidation) and would increase CO2 dissolution into colder oceans. Lower sea level and temperature would restrict entry of warm Atlantic currents into the Arctic, especially as the Arctic Ocean and parts of the north Atlantic remained ice covered year-round and ocean entry channels became narrower and shallower. It may also be the case that greater global cloud cover increased Earth's albedo and was a factor in the few degrees by which global temperatures were lowered. These effects would further enhance NH glaciation begun by insolation and ice albedo changes. These considerations might also explain why smaller insolation changes, such as occurred ~105 and 85 Kyr ago only brought the NH partially out of glaciation, and subsequent insolation dips strengthened the glaciation. Once entered, extensive glaciation would require significant NH warming before it reversed.

Ice core data indicate that temperatures in Greenland and Antarctica between the last interglacial 120 Kyr ago and glacial maximum ~20 Kyr varied over ~18 deg-C. This is much more than the few degrees of cooling experienced by the world as a whole. Lessening the total insolation absorbed by the whole Earth is necessary to lower global temperatures. This necessity is because during times the NH receives lower insulation (as 115 Kyr ago), the SH receives enhanced insolation, and insolation at the top of the atmosphere for the Earth as a whole remained relatively constant. The most obvious way to lower global temperature is by increasing Earth's overall albedo, such as with increased ice and cloud cover.

It is characteristic of glacial cycles that the exit from glaciation occurred much faster than the time to reach glacial maximum (which last occurred ~20 Kyr ago). Once glacial melting began ~18 Kyr ago, increases in global temperature and sea level and decreased ice albedo apparently created a near run-away effect, with much of the glaciers melting over a period of only ~8 Kyr. Several reasons for rapid glaciation exits have been suggested, and they may all be true in part. Apparently at glacial maximums, the cold, glaciated conditions become no longer sustainable, such that a glaciation exit can be triggered by a relatively large insolation increase – a cold trigger in reverse.

To summarize all this, the Ice Age was produced by a multi-step process.

1.) Favorable conditions were initiated ~50 Myr ago with land masses moving away from Antarctica, permitting circum-Earth ocean currents and increased Antarctic ice cover.

2.) The temperature decrease was promoted further by continually decreasing atmospheric CO2, possibly promoted by expanded continental shelves and enhanced precipitation of organic carbonates.

3.) A few Myr ago, global temperature had fallen sufficiently low that extreme insolation variations in the NH produced by Earth's orbital variations allowed winter snowfall in the far NH to survive summer melting and develop into ice cover.

4.) The growing NH glaciers decreased NH albedo and insolation heating, accelerating the NH temperature decrease.

5.) NH temperature was decreased further by increased sea ice and lowered sea levels blocking entry of warm Atlantic currents into the Arctic region. Growing land and sea ice, possibly augmented by increasing cloud cover over the whole Earth, likely increased global albedo in order to cool the entire globe.

6.) The NH hemisphere ice cover and temperature were then dominated by the cyclic nature of NH insolation produced by Earth's orbital variations, and the Earth was fully within the Ice Age.

The Future.

What about Earth's future as it leaves the Holocene interglacial.? Will we experience another glaciation cycle bringing extreme conditions in many areas for humankind? Figure 2 shows that peak insolation occurred ~10 Kyr ago and that we already are well into an insolation dip. Some proxy data indicate that Holocene temperature has been on a slow downward trend (resembling previous interglacials), and that 6-8 Kyr ago summer temperature was about one degree warmer than over the past few centuries. My prediction is that there will NOT be a new glaciation, but that global temperature and sea level will remain relatively constant over the next several tens of Kyr. The reason is that we have entered a period in which NH insolation varies only little (Fig. 2), with no large increases or decreases, in contrast to insolation changes over the past several hundred Kyr. (An extensive period with low orbital-driven insolation changes last occurred almost 500 Kyr ago.) In future, there will be no cold trigger sufficient to initiate year-long ice accumulation in the upper NH.

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