Earth 2020

An Insider's Guide to a Rapidly Changing Planet

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Ice

Julian Dowdeswell

With an average surface temperature of 15°C (and rising), much of our planet is inhospitable to ice. Today, less than 2% of Earth's water exists in a frozen form, locked up in glaciers and ice sheets, sea ice and permafrost. This 'cryosphere' is critically important for controlling global sea level and the distribution of the planet's fresh water, yet it has always existed in a rather perilous state. In contrast, the ice caps on Mars and the frozen surface of Jupiter's moon, Europa, enjoy a much colder and more stable existence. To understand the impacts of climate change on Earth's cryosphere, it is necessary to examine the different components of our icy world separately, for each has its own sensitivity to local and global forces.

Land-based glaciers and ice sheets develop when winter snowfall persists through successive summers, building up and compacting under its own weight into frozen layers that may be hundreds and sometimes thousands of meters thick. Inputs of snow on the ice-sheet surface are balanced by losses in the form of basal melting and iceberg production at ice-sheet marine margins and, in some milder areas, by surface melting and water runoff. Because of their origins from snow, glaciers and ice sheets contain fresh water. In total, about 70% of the planet's fresh water is presently locked away in these glaciers and ice sheets.

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Today, the great ice sheets of Antarctica and Greenland cover areas of 13.7 and 1.7 million km^2, respectively. The Antarctic ice sheet has an average thickness of about 3 km and a maximum of almost 5 km, with an approximate total ice volume of 30 million km^3. On Greenland, ice reaches about 3 km deep and encompasses a total volume of about 3 million km^3. Beyond these two great ice sheets, smaller ice caps and glaciers are present on many Arctic and Antarctic islands and in mountain chains around the globe, from the Himalayas and European Alps to the South American Andes. Together, these smaller ice masses cover about 700,000 km^2 (about 0.1%) of Earth's land surface.

Ice sheets and glaciers are not static entities, frozen in time and place. Rather, they are dynamic structures that move in response to various forces, including their own massive weight. Although ice exists as a solid, it deforms and flows slowly under pressure, similar to a metal that softens as its melting point is approached. In response to gravitational forces, glaciers flow by internal deformation at speeds of just a few meters per year, moving down-slope from higher elevations towards sea level. Glacier flow can be many times faster than this, however. Continuously fast-flowing ice streams within ice sheets, and so-called 'surging glaciers', where fast flow is intermittent, can move at hundreds and sometimes even thousands of meters per year when lubricating water reduces friction at their beds. Where ice sheets reach the sea, large table-like icebergs are broken off from edges of ice sheets. These icebergs, with underwater keels sometimes hundreds of meters deep, can drift for hundreds and sometimes several thousands of kilometers, well beyond the icy coasts where they originated. Icebergs from Antarctica have occasionally been observed off New Zealand's South Island, and Arctic icebergs often travel south into the North Atlantic, creating hazards for unfortunate ships such as the *Titanic*.

Compared to land-based glaciers and ice sheets, sea ice is much more variable in distribution and thickness over annual cycles. In the polar oceans, the sea-surface freezes each winter to produce ice that extends over about 15 and 19 million km^2 of the Arctic and Southern oceans, respectively. Unlike glaciers and ice sheets, much of this sea ice is short-lived, with a large portion of it melting each summer to give a minimum extent of about 4 to 5 million km^2 in the Arctic and approximately 3 million km^2 in the Antarctic. The edge of the sea ice retreats poleward as the summer proceeds, with protected fjords and inlets often being the last to become clear of ice. As a result of the seasonal cycle of ice growth and melting, sea ice is usually only a few meters thick at most, as compared to hundreds or thousands of meters for glaciers and ice sheets.

A third type of ice is permafrost, which occurs in polar and high-mountain areas where the ground is permanently frozen to depths of ten to hundreds of meters. In summer, ice in the upper meter or so of the soil matrix melts to produce a soft 'active layer', which refreezes again each winter. Permanently frozen ground occupies vast areas of the Arctic beyond the margins of modern glaciers and ice sheets, including much of northern Canada, Alaska and Siberia. When taken together, almost 23 million km^2 of the land area of the Northern Hemisphere (approximately 5% of Earth's total surface area) is covered with permafrost. This value does not include sub-sea ancient permafrost that currently sits beneath the ocean — mostly on the extensive continental shelves north of Siberia and North America. By comparison with Arctic regions, there is relatively little permafrost in Antarctica because the ice sheet covers about 99% of that continent's land area.[1]

To understand the future evolution of Earth's cryosphere, it is instructive to look to the past. For much of Earth's four-and-a-half billion-year history, the cryosphere has been strongly influenced by climate change over various timescales. Over the past billion years, there have been six cold intervals, or ice ages, during which large ice sheets existed, intermittently, over significant parts of the planet, interspersed between extensive periods when Earth was significantly warmer than it is today. In two particularly cold periods, between about 717–660 and 650–635 million years ago, geological evidence suggests the existence of a 'Snowball Earth', when most, if not all, of the planet's surface was covered in thick layer of ice.[2] The most recent cold interval began about thirty-four million years ago when ice started to build up on the Antarctic continent, in part as a response to the opening of the deep-water Drake Passage between the Antarctic Peninsula and South America, which allowed ocean currents and winds to partially isolate Antarctica from southward heat transfer from lower latitudes. An ice sheet of varying dimensions has been present on Greenland for at least eighteen million years, while the most recent ice age in Eurasia and North America marked the beginning of the Quaternary period about 2.6 million years ago.

Earth's climate has varied during the Quaternary with a periodicity of about 100,000 years. Each 100,000 cycle can be broken down into colder (glacial) and warmer (interglacial) intervals, and the last few of these cycles are recorded in the ice itself, most notably in an Antarctic ice core over 3 km long. The sequential depth-layers of this ice core contain a frozen archive that preserves the recent climate history of Earth, including temperature and greenhouse-gas concentrations going back about 800,000 years.[3] From this record, we know that the warm period in each glacial-interglacial cycle is typically much shorter than the cold phase, making up no more than 10–20% of the cycle. Today, we are in the most recent interglacial period, which started when the Earth began warming after the last full-glacial interval about 20,000 years ago. During this last glacial maximum, the ice sheets of Antarctica and Greenland became much more extensive, and mid-latitude ice sheets built up over North America, covering Canada and reaching down as far as the Great Lakes and New York. In Europe, Scandinavia, much of western Russia and northern Britain were buried under thousands of meters of ice. At this time, global sea level was about 125 m lower than today because of the growth of these huge ice sheets on land.[4]

The past 10,000 years or so has been a time of relatively warm, interglacial climate on Earth. Ice-core records show that the early Holocene was warmer than today, and there were also colder spikes such as a brief cold event about 8,200 years ago and a cooler period known as the Little Ice Age between approximately 1400 and 1900 AD.[5] During the past century, however, and particularly over the past few decades, there has been a marked increase in Earth's air and ocean temperature. The World Meteorological Organization reported recently that global air temperatures have risen by 1.1°C since comprehensive records first became available in the mid-nineteenth century.[6] About 0.2°C of this warming has occurred in only the five years between 2010 and 2015.

The icy world, in the form of glaciers and ice sheets, sea ice and permafrost, is particularly sensitive to atmospheric- and ocean-temperature changes. Climate records show that the polar regions, and the Arctic in particular, have warmed at roughly double the global rate.[7] This so-called 'polar amplification' results from changes in surface reflective properties, in particular where melting sea ice is replaced by darker ocean water that absorbs much greater amounts of solar radiation. Computer models suggest that this 'ice-reflectance effect' (sometimes known as ice-albedo effect) will continue over the coming decades, amplifying ongoing climate warming. The exact trajectory of that warming, estimated at between less than 2° and about 5°C by 2100, will depend on the future evolution of our economic, industrial and agricultural activities, and their impact on atmospheric greenhouse gases.[8]

Over the past four decades, the availability of comprehensive satellite-based measurements has radically changed our understanding of global ice distributions. Today, we know that many glaciers around the world, and parts of the massive Greenland and Antarctic ice sheets, are already thinning and retreating as a result of atmospheric and ocean warming. Since the first Earth Day, half a century ago, glaciers in many Arctic and mountain areas have thinned by tens of meters and undergone kilometers of retreat.[9] Furthermore, the Greenland Ice Sheet has shown a clear trend towards increased melting and mass loss since the turn of the twenty-first century, with almost the entire ice-sheet surface subjected to melting in some recent summers.[10] Summer melting is now also commonplace at lower elevations in parts of the western Antarctic Peninsula, and even the 2 million km^2 West Antarctic Ice Sheet is affected, with thinning and retreat detected using very accurate satellite radar and laser altimeters.[11]

Land-based glaciers and ice sheets hold huge volumes of water, which can be released into the ocean. The loss of mass from glaciers and ice sheets thus has enormous implications for global sea level change, which affects low-lying communities world-wide.[12] This effect, together with thermal expansion of seawater resulting from recent ocean warming, is the key control on global sea level change on timescales of decades to centuries. Between 1901 and 1990, sea level rose by 1.4 mm per year. By comparison, high-accuracy satellite altimeters show that sea level rise was 3.6 mm per year from 2006 to 2015, about 2.5 times its rate over much of the twentieth century. Predictions of future sea level increases suggest a global rise of between 0.4 m and about 1 m by 2100 for low and high greenhouse-gas emission scenarios, respectively.[13] In either case, many millions of people will be displaced globally.

A second area of major concern is the decline in Arctic summer sea-ice extent, which has been monitored systematically by satellites over the past forty years.[14] September sea-ice minima have declined from around 7–8 million km^2 to values often less than 5 million km^2 over this period. For perspective, this reduction in sea-ice surface area is roughly equivalent to the land mass of India. This decline is set to continue due to ice-reflectance feedback, and computer models predict that the Arctic Ocean will be largely devoid of summer sea ice within a few decades.[15] The loss of Arctic sea ice will exert a major influence on Arctic marine ecology and the humans that depend on it, with significant geopolitical implications linked to new shipping routes and resource exploration potential.

There is another possible, and somewhat paradoxical, consequence of sea-ice decline in a warming Arctic, which is related to the effects of sea-ice formation on ocean-circulation patterns.[16] When sea ice forms, salts from seawater are rejected from the forming crystals and released into the underlying surface waters, producing very cold and salty water masses that sink to the ocean depths. In the Labrador Sea off the coast of Greenland, this deep-water formation forms one branch of a large ‘ocean conveyer belt’ that transports heat and nutrients southward at great depth in the North Atlantic. The upper portion of this circulation is the northward return flow of warm Gulf Stream water in the top 1,000 m or so of the North Atlantic. If the formation of deep water slows or even stops (as appears to have happened more than once in Earth’s geological history), the Gulf Stream and its northward transfer of heat will also slow. This, in turn, would lead to the somewhat counter-intuitive cooling of North West Europe, or at least to a reduced warming trend.[17]

The huge areas of permafrost covering much of the Canadian and Eurasian Arctic are also vulnerable to warming. Although more difficult to measure from satellites than changing glacier extent and thickness, it appears that permafrost is responding to the enhanced Arctic warming of recent decades.[18] In most permafrost areas, ground temperatures and the rate of degradation in permafrost thickness and extent have increased over the past twenty to thirty years. This summertime melting has created challenging conditions for travel on the unstable ground, and has also begun to destabilize some built structures, such as houses and pipelines. Of potentially wider significance, a deepening of the biologically active upper layer of permafrost will increase the rate of organic matter decomposition in the soil, releasing methane to the atmosphere.[19] Methane is about thirty times more potent than carbon dioxide as a heat-trapping or greenhouse gas,[20] so methane release from the

Arctic tundra could lead to a positive-feedback loop in global warming. A similar process may be underway in the shallow ocean sediments of Arctic continental shelves, where frozen sub-sea permafrost deposits contain large quantities of frozen methane 'clathrates' that may become destabilized under warming ocean conditions.[21]

The shrinking area and volume of ice on Earth is significant not just for the polar regions, but also has important global effects, through sea level rise, ocean-circulation changes and accelerated melting of Arctic permafrost and the associated release of methane. Predictions of the rate of change in our icy world over the next few decades depend on how far humankind is prepared to curb the continued emission of greenhouse gases. The choices we make today will determine whether global temperatures increase by less than 2°C by 2100 (if we have some success in introducing and expanding alternative energy sources such as solar, wind, hydro-electric and tidal power generation), or whether the rise will be between 3° and 5°C (if only limited steps are taken to curtail greenhouse gas emissions). The icy world will respond accordingly. Having worked in the polar regions for almost four decades, I have witnessed changes in Earth's cryosphere first hand, in terms of both glacier retreat and sea-ice decline. Once glaciers are gone, there is little we can do to bring them back. Unless we take swift action to combat climate change, much of Earth's cryosphere may one day exist only as a distant memory.

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