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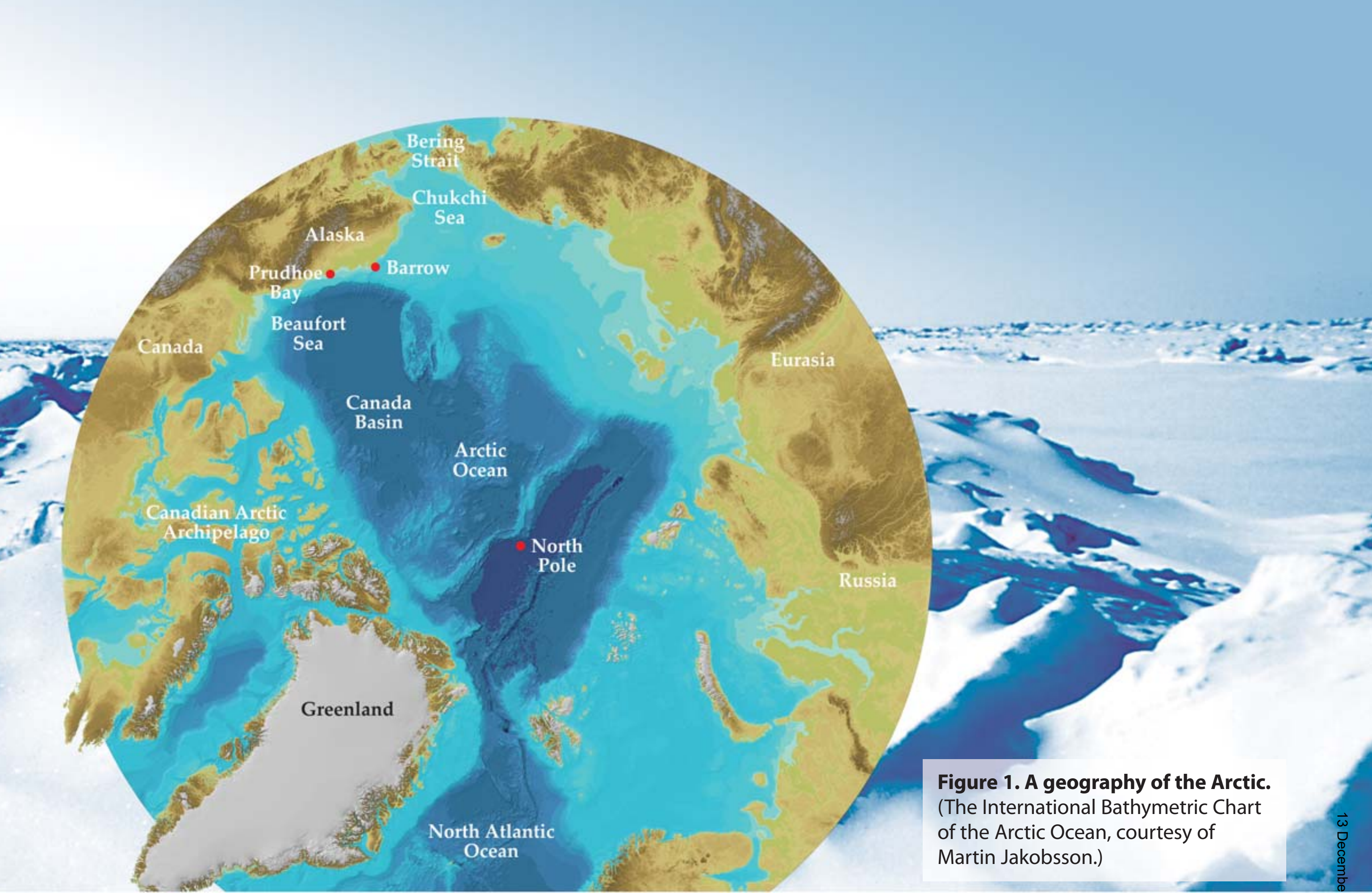

Figure 1. A geography of the Arctic. (The International Bathymetric Chart of the Arctic Ocean, courtesy of Martin Jakobsson.)

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On 5 September 1980, when the Arctic sea-ice cover reached its minimum extent for the year, it blanketed much of the Arctic Ocean and choked the inter-island channels of Canada's Arctic Archipelago. Not only did ice extend over 7.5 million square kilometers, almost equal in area to the contiguous 48 US states, but it was an old, and thus thick, ice cover: 62% was multiyear sea ice—that which survives one or more summer melt seasons—and 38% was first-year sea ice. The age and thickness of the ice made it resilient to atmospheric and oceanic forcing, such as solar radiation, storms, and air and water temperatures. Consequently, the seasonal cycle of winter advance and summer retreat was thought to be in a near steady state.

The extensive, thick ice cover that persisted through the end of the summer was considered normal at the time and for many years afterwards. It was expected of a region generally perceived to be cold, hostile, and isolated from the rest of the world, a zone of Cold War confrontation yet of little immediate consequence to most people. Northern residents would rightly have disagreed with that characterization, and multinational corporations were finding and profitably exploiting large energy and mineral reserves. The Prudhoe Bay oil field in northernmost Alaska had been producing for three years—and continues to do so—and the Polaris mine on Little Cornwallis Island in the Canadian

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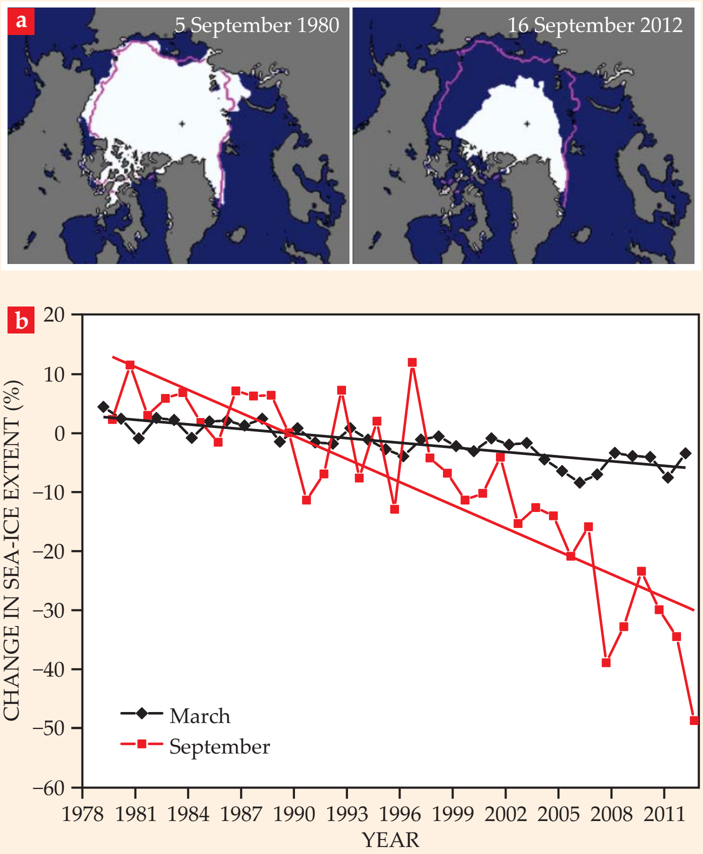

Figure 2. The decline in areal extent of Arctic sea ice has been mapped daily since 1979 by satellites using passive microwave sensors. **(a)** Between September 1980, when the summer minimum was 7.5 million square kilometers, and September 2012, when there were 3.4 million square kilometers of ice, the end of summer ice extent has shrunk by 55%. **(b)** Minimum (September) and maximum (March) ice-extent anomalies for each year are plotted beginning in 1979, when satellite observations began. Each data point represents the departure of the measured ice extent in March and September each year from the average of those months over the reference period 1979–2012. (Data are from the Sea Ice Index, National Snow and Ice Data Center; see http://nsidc.org/data/seaice_index. Walt Meier provided the plot.)

Arctic Archipelago was to begin 22 years of lead and zinc production in 1981. And scientists continued to visit, almost exclusively in the summer—rather like migratory birds—to conduct fieldwork. (See figure 1 for a map of the region.)

In October 1980 Syukuro Manabe and Ronald Stouffer (both then working at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory) reported the results of a numerical experiment on the sensitivity of global climate to a quadrupling of atmospheric carbon dioxide concentration.[1] The consequences for the Arctic were profound. Their model projected an asymmetric seasonal surface air-temperature response—greater winter warming than summer warming in the Arctic itself, and greater winter and annual warming in the Arctic than at lower latitudes. It also projected a large decline in sea-ice extent and thickness.

Whereas Manabe and Stouffer's simulation quadrupled the atmospheric CO_2 concentrations in its artificial world, the actual increase to date has been much lower. At Barrow in northernmost Alaska, for example, the mean CO_2 concentration of 385 ppm in September 2012 was only 15% higher than the 331 ppm of September 1980. And yet profound changes in surface air temperature, sea ice, and numerous other environmental conditions have occurred in the Arctic.

Retreating sea ice

On 16 September 2012, the minimum extent of sea ice was 3.4 million square kilometers, the lowest since satellite observations began in 1979 and 55% less coverage than existed in September 1980, as shown in figure 2. In September 2012 there was little sea ice in the inter-island channels of Canada's Arctic Archipelago, and in the Arctic basin the summer ice edge was distant from the Alaskan and Eurasian coasts. The 2012 ice cover was also younger and thinner, with 58% of it less than a year old. A thin ice cover is less resilient and more prone to melting and retreat in summer than a thick one. It is also more translucent and thus allows greater light transmission into the underlying ocean. One consequence is a rise in what's known as primary production—that is, photosynthesis by algae and phytoplankton—in the water below the ice and in previously ice-covered waters.

The minimum extent of sea ice is currently declining by an average of 91 600 km^2 per year, roughly equivalent to the area of Maine, or −13.0% per decade relative to the 1979–2000 average. The maximum extent, typically recorded in March, is also declining, though at a slower rate of −2.6% per decade, and in March 2013 sea ice more than a year old made up only 30% of the ice cover. The shift to a younger, thinner ice cover is due to dynamic and thermodynamic processes, but determining the relative contribution of each remains a difficult research problem (see the article by Ron Kwok and Norbert Untersteiner in PHYSICS TODAY, April 2011, page 36).

The decline in summer sea-ice extent has attracted growing media attention since 2007, when a precipitous drop shook the scientific community. That drop was followed by yet another to a new low in the summer of 2012. Indeed, the six years from 2007 through 2012 have seen the lowest ice extents in the satellite record (see figure 2b). The marked downward trend experienced in those years suggests a shift to a new normal for sea ice. Profound change is not limited to sea ice, though. A new normal is evident throughout the Arctic environment—in the atmosphere, in the ocean, and on land.

What else is changing

Global warming produces a larger effect in the Arctic than it does in midlatitudes, as shown in figure 3 and as predicted by Manabe and Stouffer.[1] (Incidentally, Swedish scientist Svante Arrhenius was the first, in 1896, to quantify the contribution of CO_2 to the greenhouse effect and to suggest greater warming in the Arctic than at lower latitudes.) Arctic air temperature increased in all seasons during the period 2000–09, with the greatest warming in autumn and winter.[2] Mean annual temperature in the Arctic is now 1.5 °C higher than the 1971–2000 average; that's more than double the warming at lower latitudes during the same period.[3]

As the sea ice has retreated, it has exposed an ever-growing area of open water to solar radiation, and ocean heating each summer has increased due to the large difference in albedo—the fraction of solar irradiance reflected by the surface—between ice and water.[4] Consequently, August sea-surface temperatures are now as much as 3 °C higher than their 1982–2006 average, and the upper-ocean heat content has increased by as much as 25% in the Canada Basin's Beaufort Gyre, compared with its content in the 1970s. The Beaufort Gyre is also the region of the greatest freshwater accumulation in the Arctic Ocean, up about 25% since the 1970s, a rise that has strengthened the stratification of the upper ocean and deepened the halocline.[3]

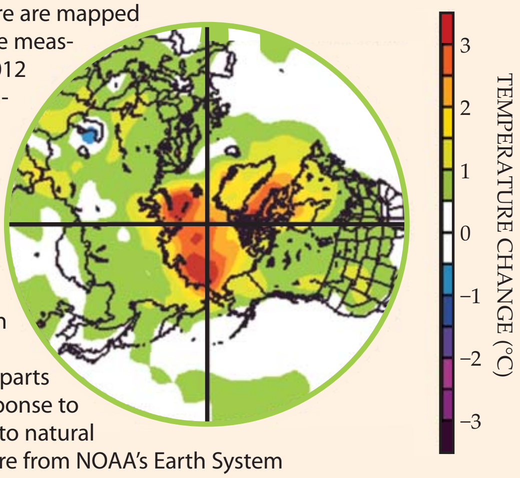

Figure 3. Annual near-surface air temperature changes in the Northern Hemisphere are mapped as the average temperature measured between 2001 and 2012 relative to the average temperature for the 30-year baseline period 1971–2000. Arctic temperature changes of +2–3 °C, compared with the more modest rise of +0.5–1 °C in midlatitude regions, exemplify Arctic amplification of global climate change. Higher temperatures in all parts of the Arctic indicate a response to global change rather than to natural regional variability. (Data are from NOAA's Earth System Research Laboratory, Boulder, Colorado: http://www.esrl.noaa.gov/psd.)

The halocline is the upper-ocean layer in which a strong salinity gradient and near-freezing temperatures maintain the water column's stability, which keeps apart the cold surface waters and sea ice above from the warmer Pacific and Atlantic waters below. In the Canada Basin, the halocline lies at depths of 50–150 m, just above Pacific water that enters the Arctic Ocean through the Bering Strait,[3] where oceanic fluxes of heat and freshwater have increased by some 50% since 2001.

Sea ice is integral to the marine ecosystem, and its decline has biological consequences. Satellite measurements, shown in figure 4, reveal a roughly 20% overall increase in ocean primary production between 1998 and 2009, mostly on the Eurasian side of the Arctic Ocean due to increases in the extent and duration of open water.[5] Unexpectedly massive under-ice phytoplankton blooms, found in July 2011 to extend at least 150 km into consolidated pack ice in the Chukchi Sea, suggest that previous estimates of annual primary production might be 10 times too low in waters where such under-ice blooms occur.[6] The blooms might benefit from sea-ice melt ponds acting as skylights that channel solar radiation to the water below the ice.

In the Canada Basin, by contrast, the strengthening of upper-ocean stratification and deepening of the halocline may be limiting primary production. Coupled with the uptake of atmospheric CO_2, the reduced primary production probably accounts for the acidification of surface waters in the Canada Basin.[7]

Researchers looking at the other end of the biota size scale find that the loss of sea-ice habitat is negatively affecting certain marine mammals. Walruses, for instance, have increasingly limited access to summer sea-ice cover where they normally rest while feeding in shallow continental-shelf waters near the coasts of Russia and Alaska; instead, they are going ashore in large numbers along the Chukchi coasts of

Arctic amplification and lower-latitude weather

Due to positive feedback, a modest rise in temperature at Earth's midlatitudes leads to a greater temperature rise in the Arctic. But such amplification in the Arctic can, in turn, affect the weather at lower latitudes. For instance, record winter snowfalls and low temperatures recently experienced in Earth's midlatitudes are thought to arise in part from the heating in autumn and early winter of the Arctic troposphere—the lower roughly 10 km of its atmosphere. The weather extremes are driven by changes in wind patterns caused by the warming temperatures over areas of the Arctic Ocean free of sea ice. The winds enhance the southerly transfer of relatively colder Arctic air masses.[15] Some researchers argue that such Arctic forcing, while controversial, increases the north–south amplitude of the polar jet stream and reduces its wind speed.[16]

The result is slower-moving weather systems in midlatitude regions and a higher probability of extreme events, such as cold spells and heat waves, flooding and drought, and Greenland ice-sheet melting.[16] The eastern US, northern Europe, and far-eastern Asia seem particularly prone to such Arctic influences. Although the increased forcing from the Arctic is well documented, the processes that link Arctic forcing to the more chaotic atmospheric flow in midlatitudes are more speculative. Mechanisms for Arctic amplification and potential weather effects in lower latitudes have been documented in recent scientific articles, and they remain a major area of Arctic climate research.

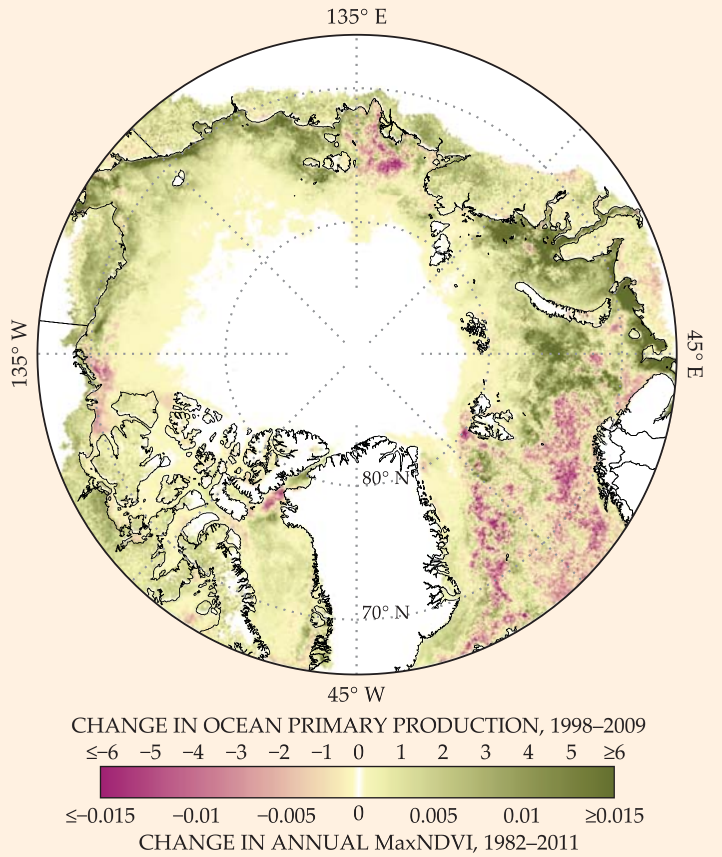

Figure 4. The maximum Normalized Difference Vegetation Index (MaxNDVI) is a measure of vegetation greenness observed from space. It is also a proxy for aboveground biomass at the peak of the growing season. Shown here is the change it underwent from 1982 to 2011 and, with the same color bar, the change in total annual primary production—a measure of photosynthesis by algae and phytoplankton in units of grams of carbon per square meter per year—over the period 1998–2009 in the Arctic Ocean and adjacent waters. (Adapted from ref. 3, prepared by Karen Frey and Uma Bhatt.)

Russia and Alaska, farther from the feeding grounds. There is also evidence for the migration of mollusk, crab, and fish species northward through the Bering Strait. A shift to an ecosystem whose food web is spread throughout the water column rather than localized on the sea bottom of the Chukchi Sea[8] would favor species such as bowhead, fin, humpback, minke, and blue whales, while bottom feeders, such as walruses, bearded seals, and diving ducks, would be disadvantaged.

On land, snow-cover duration is declining in North America and Eurasia, primarily due to earlier spring melt, which reduces the land surface albedo.[9,10] As terrestrial snow cover and sea ice have retreated and the sea surface has warmed, tundra greenness and aboveground biomass (see figure 4), particularly shrubs, have increased.

Change is also occurring belowground. A steady increase in permafrost temperature on the North Slope of Alaska exemplifies a circumpolar trend that has been evident since the mid-20th century.[3] What's more, the warming has coincided with observations of large fluxes of methane, a potent greenhouse gas, to the atmosphere from terrestrial and offshore sources. Reassuringly, though, evidence to date indicates that natural methane emissions in the Arctic have not risen significantly in the past decade.[11]

Glaciers, ice caps, and the Greenland ice sheet are rapidly losing mass (see figure 5), a worrisome trend given their potential role in sea-level rise. On the Greenland ice sheet, the area and duration of melting have been increasing, and the surface albedo has been decreasing[7] since satellite observations of the two effects began in 1979 and 2000, respectively. Strong advection of warm air from the south in recent summers has contributed to the extensive surface melting and mass losses from the Greenland ice sheet and Canadian Arctic glaciers and ice caps.[3]

Sources of Arctic amplification

Manabe and Stouffer did not use the term, but the strong, all-season temperature response in the Arctic to CO_2-induced global warming is now commonly referred to as Arctic amplification. As mentioned earlier, the actual increase in Earth's atmospheric CO_2 and other greenhouse gas levels since 1980 is a small fraction of that used in the Manabe–Stouffer model. The disparity raises the question of what drives the amplification. The short answer is modest external forcing from midlatitudes combined with multiple positive feedbacks within the Arctic system itself; for more details, see the accounts by Mark Serreze and Roger Barry[2] and by Julienne Stroeve and her coauthors.[4]

The spatial synthesis of atmospheric data, known as reanalysis fields, offers evidence that the poleward transport of energy in the troposphere leads to higher Arctic air temperatures at the surface, particularly in winter. Satellite measurements indicate that the heat flux into the Arctic is accompanied by an increase in cloud cover and water vapor. Clouds amplify the effects of surface warming by augmenting the net downward long-wave radiation flux and the greenhouse effect of water vapor (see the article by Bjorn Stevens and Sandrine Bony in PHYSICS TODAY, June 2013, page 29), particularly in winter and spring. Model studies indicate that the warming might be further enhanced by the rise in atmospheric concentrations of carbon aerosols, known as black carbon or soot, which also absorb solar radiation. Black carbon deposition might be reducing the albedo and thus accelerating the melting of sea ice and of snow and ice on land.

The poleward transport of atmospheric heat and moisture causes local changes in the sea-ice cover and other Arctic-specific variables. Higher air temperatures at the surface reduce winter sea-ice growth rates; the thinner cover is then more vulnerable to melting in spring. Areas of dark (low-albedo), radiation-absorbing open water, in turn, lead to further melting. The increase in the ocean's heat content inevitably delays the autumn freeze.

Ponds of meltwater that accumulate on the sea ice absorb an increasing amount of solar radiation as they grow larger, which leads to further melting

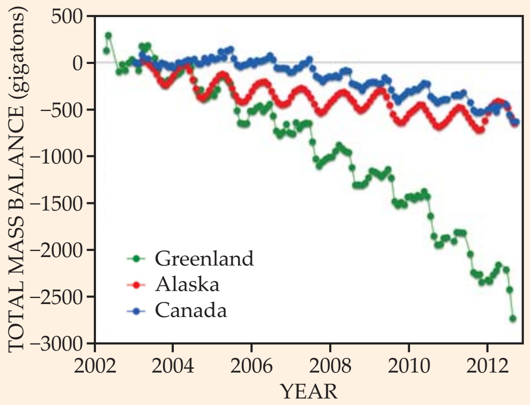

Figure 5. The Greenland ice sheet and glaciers and ice caps in the Gulf of Alaska region and the high Canadian Arctic have been losing mass, by melting and iceberg calving, since *GRACE* satellite observations began more than 10 years ago. Mass loss, in gigatons, from the Greenland ice sheet is accelerating and is currently almost three times the combined total loss from the Alaskan and Canadian sources. The seasonal cycle of winter snow accumulation and summer melting is evident in the oscillations recorded from each region. (Adapted from ref. 7, prepared by Marco Tedesco and Gabe Wolken.)

over the course of a summer. The albedo effect also applies to glaciers and snow on land. On the Greenland ice sheet, for example, the decreasing albedo of the ice surface promotes further melting and runoff, an effect enhanced by a decline in summer snowfall. On land, atmospheric warming leads to earlier snow melt in late spring and exposure of the darker land surface. That exposure, in turn, further warms the surface and the atmosphere above it.

The transport of Atlantic and Pacific waters also provides heat to the Arctic. However, those water masses flow many tens of meters below the surface, and the processes by which the heat would reach the surface of the highly stratified upper-ocean water column remain to be determined. A new upper-ocean feature is the so-called near-surface temperature maximum. Originating from solar warming in summer, the NSTM is residual heat that has survived autumn cooling and has the potential to melt ice in the subsequent winter and reduce the maximum ice thickness.

The combination of external forces and regional feedbacks doesn't alter only the Arctic environment. Interestingly, growing evidence suggests that changes in the Arctic have their own effects at lower latitudes, as outlined in the box on page 37.

Socioeconomic consequences

The Arctic Ocean and adjacent subarctic seas supply food for indigenous peoples whose culture and traditional way of life are affected by the prevalence of open water. They now must travel farther offshore—over more unstable ice or through increasingly rough seas—to hunt mammals that live in icy habitats. The wave action on thawing and vulnerable shorelines accelerates the coastal erosion and is affecting village, archaeological, and sacred sites. In Alaska, the estimated cost of relocating a single village farther inland is on the order of $100 million.

Roads, railways, runways, pipelines, harbors, and homes are all vulnerable to effects of warming in permafrost-rich regions. Yet the demand for new construction and its impact on residents and the environment will only rise with the predicted increase in oil, gas, and mineral extraction efforts. Recognizing a growing interest in an Arctic Ocean fishery, the US declared a moratorium on commercial fishing in its Arctic waters in 2009, citing the need to learn more about fish stocks and the ecosystem.

Maritime transportation, including cruise-ship traffic and summertime trans-Arctic shipping that takes advantage of the shorter distance between Europe and Asia, is also expected to rise. The prospect of increased vessel traffic and natural resource extraction indicates the need for other types of supporting infrastructure and capabilities—for instance, maritime domain awareness, oil-spill prevention and response, search and rescue, and communications—in a region where they are severely limited. Some people predict that global competition for natural resources will lead to confrontation, instability, and militarization. Others doubt such consequences in a region where governance is considered to be strong.

Whither the Arctic?

The Arctic environment is highly sensitive to increases in global mean temperatures and ultimately to the continuing increase in atmospheric CO_2 concentration. That sensitivity is manifest as large and persistent physical and biological shifts relative to previous observations and suggests a new normal for the Arctic environmental system.

For all the evidence of system-wide environmental change, the Arctic remains a data-sparse region. Observations are far from comprehensive; the infrastructure required to make them—for instance, weather stations, stream gauges, and snow courses—is often threatened with diminishment or outright shutdown, and open data access has yet to be universally adopted. As a result, opportunities to detect change will remain limited, as will our understanding of the processes behind it and our ability to forecast the future. Those are all problems that frustrate public and private planners, managers, and policymakers who must make decisions based on the Arctic's new normal environmental state.

For example, it's been known for years that the observed rate of sea-ice retreat exceeds the rate simulated using climate models. And despite a great deal of effort that has gone into improving the models in preparation for the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change, the spread among the current generation of models remains large,[12] as shown in figure 6.

Indeed, an extrapolation of the trend in sea-ice volume estimates suggests that nearly ice-free Arctic summers could become the norm as soon as a decade or so.[13] By contrast, models that form the basis for AR5 predict that won't happen until mid century (roughly 2060, according to the median line in figure 6). The gap is relevant for policymakers: The observation-based estimate lends an urgency to the issue of

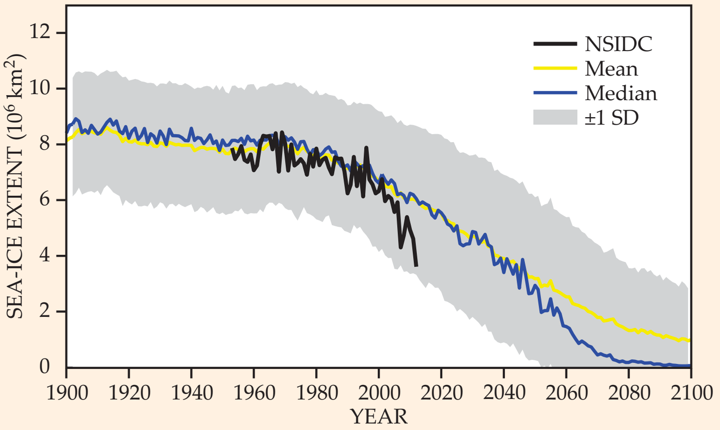

Figure 6. Sea-ice extent is declining faster than models predict. The large spread of ±1 standard deviation (SD; gray) in 84 predictions of ice extent from 36 different current models underscores the uncertainty about the future state of the ice cover and the need to improve our understanding of air-ice-ocean processes and their representation in the models. These and similar results form the basis for the fifth assessment report of the Intergovernmental Panel on Climate Change. The black curve plots observational data dating back to 1953 from the National Snow and Ice Data Center (NSIDC). The yellow and blue curves are the mean and median of the model results, respectively. (Adapted from ref. 13.)

responding to climate change; the model-projected estimates do not. Many Arctic scientists consider that although the models provide qualitative support for Arctic amplification and future sea-ice loss, they have limited value for quantitative projections. Model deficiencies in ocean circulation, cloud physics, atmospheric dynamics, and albedo parameterization—details that go beyond sea-ice physics per se—all contribute to the spread among model predictions.

Therefore, improving observations, understanding, and models of sea-ice, ocean and atmospheric processes, interactions, and feedbacks are among the numerous goals identified for immediate action in the US Interagency Arctic Research Policy Committee (IARPC) research plan.[14] Released in February 2013, the five-year plan focuses on seven broad research themes most likely to benefit from better communication and coordination among federal agencies and from partnerships with the State of Alaska, local communities, indigenous organizations, nongovernmental groups, and the academic community. The IARPC plan has grown in significance with the release by the Obama administration in May 2013 of its *National Strategy for the Arctic Region*, which stresses the need to increase understanding of the Arctic through research that will support decision making informed by the best available scientific information.

The IARPC plan and the *National Strategy* also emphasize the need for the US to work with international partners. Such cooperation is exemplified by the Distributed Biological Observatory (DBO), which consists of six biological "hot spots" that extend from the northern Bering Sea through the Chukchi Sea to the western Beaufort Sea. The DBO sites are maintained by the Pacific Arctic Group of six countries—Canada, China, South Korea, Japan, Russia, and the US—all of which have agreed to make and share a standard set of biophysical measurements whenever one of their research vessels enters a hot spot. Another consortium, International Arctic Systems for Observing the Atmosphere (IASOA), which promotes data access and coordinated atmospheric observations of, among other things, greenhouse gases, clouds, energy fluxes, pollutants, and aerosols, also exemplifies good observing practice and data policy.

The DBO and IASOA contribute to Sustaining Arctic Observing Networks (SAON), a joint activity of the Arctic Council (the representatives of eight Arctic countries and indigenous peoples) and the nongovernmental International Arctic Science Committee of 21 national member organizations. The goal of SAON is to encourage partnerships and synergies among observation and data networks and to promote the sharing and synthesis of data and information.

In 1980 much Arctic science was motivated by Cold War confrontation as the US and the Soviet Union faced each other across the Arctic Ocean. Then, even at the end of the summer, the Arctic Ocean remained a largely ice-covered barrier. Today the motivation for Arctic science and the geopolitical situation have changed. The retreat of the sea ice and opening of the Arctic Ocean, their role in Arctic amplification of global warming and its impact on lower latitudes, and the socioeconomic and geopolitical ramifications of the new normal in the Arctic are feeding the need for international collaboration in policy as much as in science.

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