Satellite-Observed Changes in the Arctic

The Arctic has warmed by about 1°C in the past two decades. That time period has seen glaciers retreat, permafrost thaw, snow cover decrease, and ice sheets thin.

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The Arctic is one of the most inaccessible areas on Earth. Extreme cold and adverse weather make the region inhospitable, and its central component, the Arctic Ocean, is covered by sea ice that is, on average, about 2–3 meters thick. That ocean spans 14 million square kilometers and is bordered by Russia and Europe on the east and Alaska, Canada, and Greenland on the west.

The Arctic plays important roles in Earth's climate system. It serves as an energy sink and could provide an early signal of climate change because of feedbacks associated with the high albedo and insulation effects of the snow and ice that blanket much of the region.[1] A warming trend, for instance, may diminish the snow-covered areas, which then reflect less of the incident solar flux, thus triggering further warming. In an era when anthropogenic global warming is a contentious issue, studies of the Arctic are increasingly important. Scientific reports over the past several years have indicated substantial and coherent physical changes to the Arctic's glaciers, permafrost (frozen soil), and snow- and ice-covered areas.

Some of the reported changes, though, are based on few and sparsely distributed measurements, so they are hardly representative of the pan-Arctic system. Only after the development of satellite remote sensing could researchers monitor the full Arctic. And although the first satellite was launched in the late 1950s, it wasn't until the 1970s that multichannel sensors were introduced onboard and researchers could accurately measure Arctic surface parameters such as sea-ice concentrations, albedo, or surface temperatures (see the box on page 40). The data from those satellites over the past 30 years have provided a record of almost the entire region (except a small, pole-centered area sometimes missed because of orbit inclination) from which one can study intriguing anomalies and trends in the continuing evolution of the Arctic system.

Surface warming

One of the more critical parameters to monitor for physical changes is surface temperature. In regions where the temperature is near the freezing point, slight fluctuations can make a major difference in whether ice and snow covers will increase or melt away. A change of even a few days in the onset of melting or freezing can matter.

With satellite thermal-IR radiometers, climatologists can investigate spatial as well as temporal variability in surface temperature during clear sky conditions. Since August 1981, scientists have used the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) to derive monthly surface temperatures in the Arctic.

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Figure 1 illustrates the differences that have emerged over two decades; to distinguish the subtle changes, one set of 11-year averages is subtracted from a subsequent set of 11-year averages. In nearly all areas of the Arctic—except parts of Russia—the surface was warmer in the more recent decade. And the differences in the amount of warming from one area to another are generally consistent with trends for the Arctic previously reported for a shorter period.[2] The asymmetric patterns in figure 1c are probably associated with similar patterns in wind circulation that change periodically from cyclonic to anticyclonic modes.

Based on linear regression analysis of the AVHRR data, surface temperatures at latitudes higher than 60°N between 1981 and 2003 increased at an average rate of about half a degree celsius per decade. More specifically, warming occurred at about 0.54°C per decade over sea ice, 0.85°C per decade over Greenland, and 0.79°C per decade over North America, and cooling occurred at about 0.14°C per decade over Eurasia, with uncertainties of about ±0.2°C per decade in each case. To appreciate how satellite monitoring improved on prior records, consider the trend over North America calculated for 1981–2003 using the relatively sparse in situ data set previously collected.[3] That limited data set yields a trend of 0.39°C per decade, which underestimates by about one-half the warming that the region really experienced. The AVHRR data, restricted to the same regional points, produced a similar underestimation.

Based on the full satellite data, the warming trends varied considerably with season, by as much as several tenths of a degree per decade for the high altitude areas (>60°N), between 0.84°C per decade in spring and 0.25°C per decade in summer. Winters in Eurasia produced most of the cooling in that area (−0.56 ± 0.69°C per decade). Among the effects of the net surface warming is a lengthening of the melt season by a few days—almost three days per decade over sea ice and four days per decade over Greenland, for instance.

Atmospheric change

The troposphere is the lowest layer, 8–16 km high, of the atmosphere and has temperatures that generally decrease with altitude. This layer is the most important for life at Earth's surface and includes most of Earth's clouds and water vapor. To study changes in the troposphere, scientists use the *TIROS* Operational Vertical Sounder (TOVS) combined with a reanalyzed data set from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR).[4] The sounder's multichannel measurements compare well with "radiosonde" data gathered from balloon-based instruments, which measure vertical profiles of temperature, pressure, and humidity. Since 1979, researchers have used the TOVS data to characterize horizontal vari-

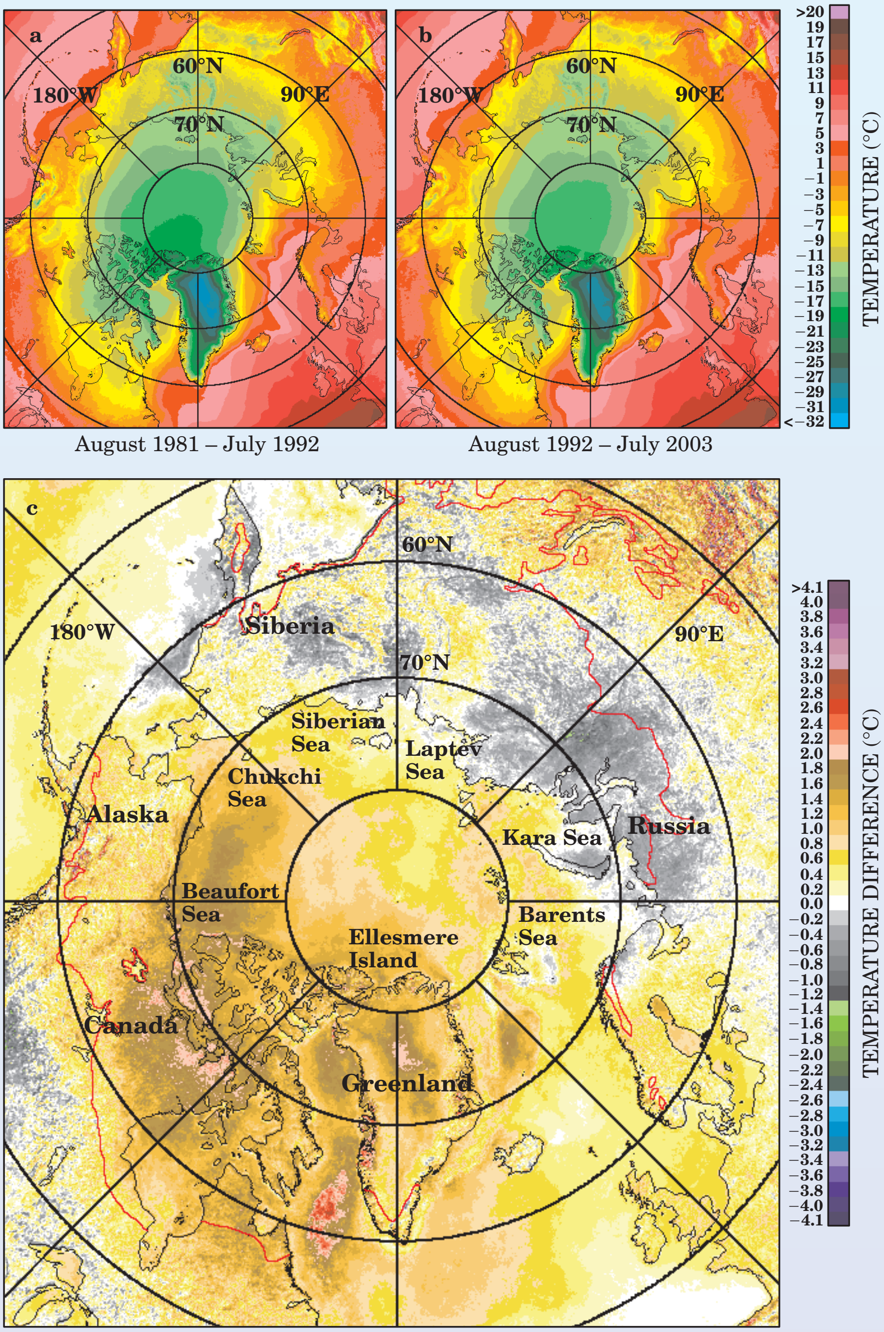


Figure 1. Surface warming is evident from 22 years of IR data collected using the National Oceanic and Atmospheric Administration's series of polar-orbiting satellites: **(a)** average surface temperature from readings taken between August 1981 and July 1992 and **(b)** average surface temperature from August 1992 through July 2003. **(c)** Subtracting the first set of data from the second reveals the net warming trend. The red line represents the southern boundary of the discontinuous permafrost. (Adapted from ref. 2; red-line data courtesy of the United Nations Environment Programme.)

ations and gradients in temperature and the NCEP/NCAR reanalysis data to study trends and confirm some of the measurement variations in time. That scheme was implemented because of uncertainties in the calibration of TOVS. The results of the combined analysis indicate that particularly large changes occurred near the end of the 1980s in the western Arctic in spring.

In general, springs were warmer and came earlier in the 1990s than in the 1980s. Such warming is clearly illustrated by the map showing the differences between averages of spring tropospheric temperatures in the 1980s and those in the 1990s (see figure 2a).[4] On the other hand, figure 2b shows a cooling trend, based on TOVS data for the same period, but higher up, in the lower stratosphere.

The stratosphere lies just above the troposphere and extends to an altitude of about 50 km. The ozone in that atmospheric layer protects terrestrial life by absorbing UV radiation from the Sun. And that absorption forms the basis by which satellite UV radiometers detect ozone from space. The Total Ozone Mapping Spectrometer (TOMS), in particular, has provided a record of atmospheric ozone since the launch of the *Nimbus 7* satellite in 1978. Figures 2c and 2d illustrate the differences in ozone levels recorded (see PHYSICS TODAY, January 1998, page 18).

The decay of stratospheric ozone is a complicated dynamical and chemical process generally aided by low stratospheric temperatures and the concomitant formation of polar stratospheric clouds. It is highly variable from year to year and depends in large part on the existing chemical and thermal conditions and also on planetary waves—disturbances thousands of kilometers long with wavelengths the size of cyclones—that affect (or "force") those conditions.[5] Overall, the Arctic stratosphere has become colder in recent decades (see figure 2b), a trend that has hastened the destruction of stratospheric ozone. Less ozone, in turn, leads to further stratospheric cooling because UV radiation is less effectively absorbed.[6]

The ozone levels in the Arctic were measured using TOMS and the *ERS-2* (*European Remote Sensing* satellite) Global Ozone Monitoring Experiment (GOME) over the period November 1978–December 2000. The data indicate ozone loss of about 1% per year in February, March, and April, with no statistically significant trends measured during the other nine months. By comparison, the Antarctic experienced a 2.4%-per-year decrease in ozone in October, generally the month in which its ozone hole is the most pronounced.[6] Although ozone-depleting chemicals are no longer increasing in the stratosphere as a result of the 1987 Montreal Protocol and subsequent international agreements, ozone could continue to decrease if the stratosphere continues to cool, an outcome that is expected based on greenhouse-gas simulations.

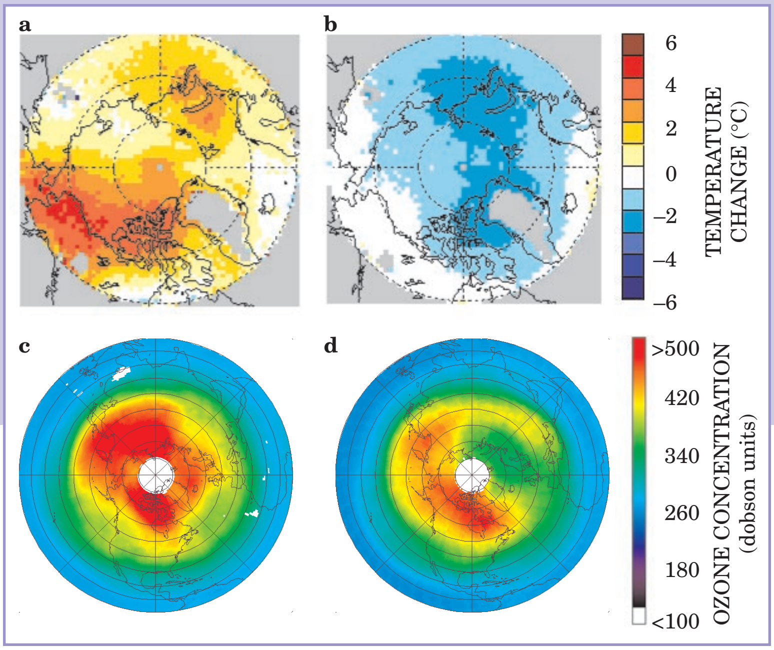


Figure 2. Springtime temperatures in the troposphere **(a)** warmed on average from the 1980s through the 1990s, especially in the western part of the Arctic, as recorded by the *TIROS* Operational Vertical Sounder (TOVS). A cooling trend in the stratosphere occurred in springtime during the same period **(b)**. The Total Ozone Mapping Spectrometer measured different ozone levels in the Northern Hemisphere in **(c)** March 1979 and **(d)** March 2003. The unit of measure in ozone research is the dobson unit. One DU corresponds to a layer of ozone that would be 0.01 millimeters thick if brought to standard temperature and pressure (0°C and 1 atmosphere). (TOVS images from Overland et al., ref. 4; ozone images from data available at http://toms.gsfc.nasa.gov.)

Melting ice sheets and glaciers

The largest land ice mass in the Northern Hemisphere is the Greenland ice sheet, which covers about 1.7×10^6 km^2, or 80% of the island. An additional 3% is covered by smaller glaciers and ice caps. The ice sheet is 1.7 km thick on average, with a total volume of ice that, if entirely melted, would increase Earth's sea level by about 7.2 m. Such a catastrophe is not imminent, but the volume of ice and its relevance to sea level make monitoring the ice sheet an important priority.

Over the past decade, regular flights over Greenland using NASA aircraft equipped with a light detection and ranging system have produced measurements showing the ice sheet to have thinned by as much as 1 m in some locations around the periphery.[7] The lubrication of ice layers and their spreading or compression as they slowly flow account for some of that thinning, which leads to some redistribution of the mass. The most visible change appears to be in the melt distributions in Greenland, a change readily observed from passive microwave satellite data. Those

Satellite Data and Inversion Techniques

The best platforms for observing changes in the Arctic as a whole are polar-orbiting satellites, the first of which were launched in the 1960s. Some satellites are equipped with a variety of sensors that record data at different frequencies, from UV to visible, IR, and microwave. The sensors can be passive or active, depending on the mode of operation. Satellite sensors provide coverage of the full Arctic region and can monitor the surface at a relatively high temporal resolution: every 100 minutes for the highest latitudes and several times a day for lower Arctic latitudes. Processing the data involves using inversion algorithms that convert satellite-measured radiances into geophysical parameters. This inversion technique takes into account atmospheric effects on the radiation and spatial variations in the surface emissivity and backscatter. The design of such a technique requires an understanding of the emission characteristics of the surface of interest and how the measured radiation is affected by the atmosphere.

The basic radiative transfer equation that applies to the brightness temperature T_B recorded by satellites at a given wavelength is

$$T_B = \varepsilon T_S e^{-\tau} + \int_0^{\tau} T(z)\,\zeta(z)\,e^{-\tau+\tau'(z)}\,d\tau'(z) + (1-\varepsilon)\kappa e^{-\tau}\int_0^{\tau} T(z)\,\zeta(z)\,e^{-\tau'(z)}\,d\tau'(z), \tag{1}$$

where ε is the emissivity of the surface; T_S is the physical temperature of the surface; T(z) is the physical temperature of the atmosphere at height z; $\tau'(z)$ and τ are the atmospheric opacities from the surface to a height z and from the surface to the satellite height, respectively; κ is an estimate of the diffusiveness of the surface reflection; and $\zeta(z)$ is the emittance at z. In equation 1, the first term on the right-hand side represents radiation directly from Earth's surface, which is often the dominant contribution for measurements at microwave frequencies. The second term represents radiation directly from the atmosphere, and the third term represents downwelling radiation from the atmosphere that has been reflected toward the satellite from Earth's surface. Radiation from free space is a negligible additional contribution so is not included.

To illustrate an inversion technique, we examine one parameter frequently used in polar studies, namely, sea-ice concentration derived from passive microwave data. For areas within the ice pack, the radiation detected by the satellite sensor comes partly from the ice and partly from liquid water. When the ice and ocean surfaces are uniform radiometrically, the observed brightness temperature is expressed in terms of the relative contribution from each surface by a linear mixing formulation:

$$T_B = T_O C_O + T_I C_I, \tag{2}$$

where T_O and T_I are the brightness temperatures of ice-free ocean and sea ice, respectively, and C_O and C_I are the corresponding fractions of each of the two surface components within the sensor's field-of-view. C_O and C_I add to unity. Equation 2 and its extension to more than one ice type form the basis for sea-ice concentration algorithms. Complications arise from temporal and spatial changes in T_O and T_I, which are both functions of emissivity ε, temperature T_S, and atmospheric opacities τ and τ', as indicated in equation 1. Such changes can be accounted for or at least minimized through the use of several passive microwave channels.

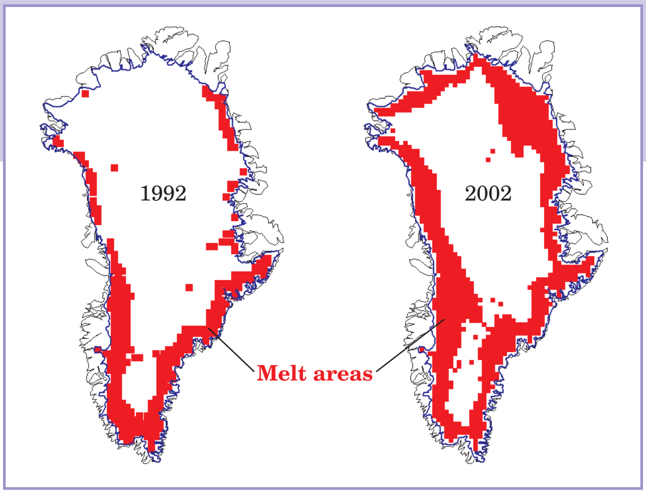


Figure 3. Differences in the expanse of summertime melt over Greenland in 1992 and 2002, illustrated in red. The blue outline delineates the border of the Greenland ice sheet. (Data courtesy of Konrad Steffen and Russell Huff, University of Colorado at Boulder.)

data show an enhanced surface signature during the onset of melt, when liquid starts forming in the snow cover. Figure 3 illustrates the 17% expansion of the melt region inferred from data taken in 1992 and 2002. Such an increase in melt area affects the character of the snow on the surface and subsurface and may be partly responsible for the ice thinning (see PHYSICS TODAY, January 2000, page 19).

Outside of Greenland, the glaciated land areas of the Arctic include many of the islands in the Canadian Arctic and the Arctic Ocean and mountainous regions of northern Alaska, northern Scandinavia, and northern Russia. Many, but not all, of those regions have experienced decreases in mountain glaciation over the past century.[8] And that decrease has contributed to the estimated 10- to 20-cm sea-level rise that has occurred since 1900.[9] Satellites can monitor such glaciers. But, because glacial processes tend, in general, to operate on longer time scales than processes in the atmosphere and upper oceans, the satellite record has been useful more for obtaining a baseline picture of glacial extent in the late 20th and early 21st centuries than for determining long-term trends.

LANDSAT imagery, in particular, has been used to create a multivolume *Satellite Image Atlas of Glaciers of the World*[8]; several volumes address Arctic areas. That work provides a baseline of global land glaciation as of the 1970s and 1980s. An international program currently uses data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the *Terra* satellite, launched in December 1999, to map the post-1999 extent of Earth's glaciers. ASTER obtains high-resolution (15- to 90-m) imagery from 14 channels at wavelengths from visible to thermal IR. The *LANDSAT* and ASTER data have confirmed a variety of changes in Arctic glaciers—with some growing, some decreasing, some oscillating, and some remaining fairly steady—although the net trend has been toward reduced glacial coverage.[8] In Alaska alone, polar-orbiting satellites are monitoring 15 000 glaciers, most of which appear to be retreating. Figure 4a shows a sample image of several glaciers on Ellesmere Island and icebergs calved into Dobbin Bay from Eugenie Glacier's floating tongue.

Among the most dramatic of the glacial ice changes in the Arctic during the period of satellite record is the major breakup between 2000 and 2002 of the Ward Hunt Ice Shelf along the northern coast of Ellesmere Island. Data from *RADARSAT*, a satellite equipped with a high-resolution imaging radar, showed no evidence of fracturing of the shelf in 1998 or 1999, a clear fracture in April 2000, and substantial decay by September 2002.[10]

Retreating snow cover and permafrost

Snow cover over land can be monitored from space using both visible or IR data and passive microwave data, although results may vary depending on which wavelength is used. The microwave data can be collected under most

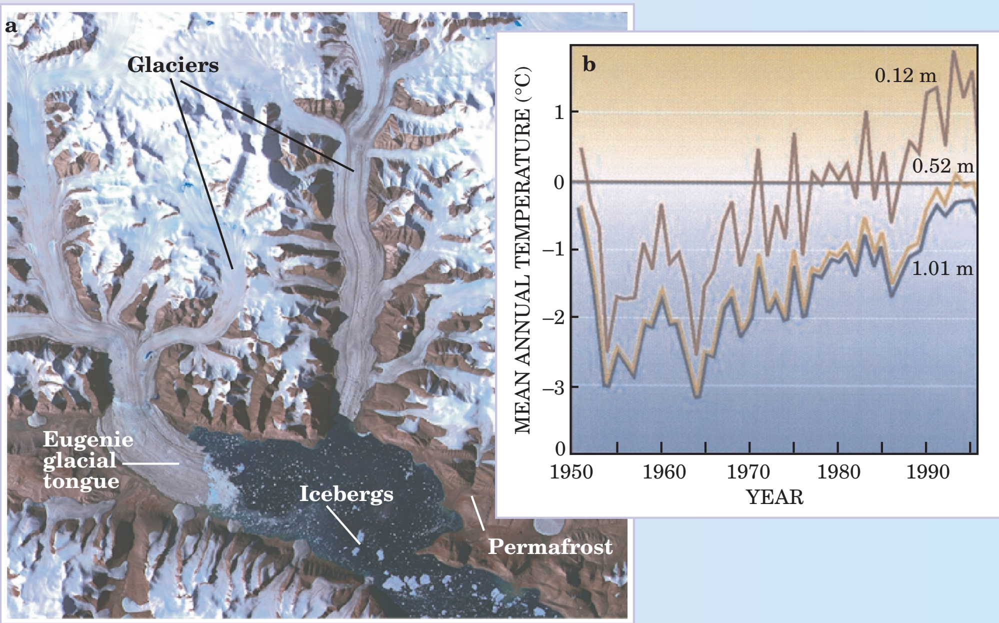
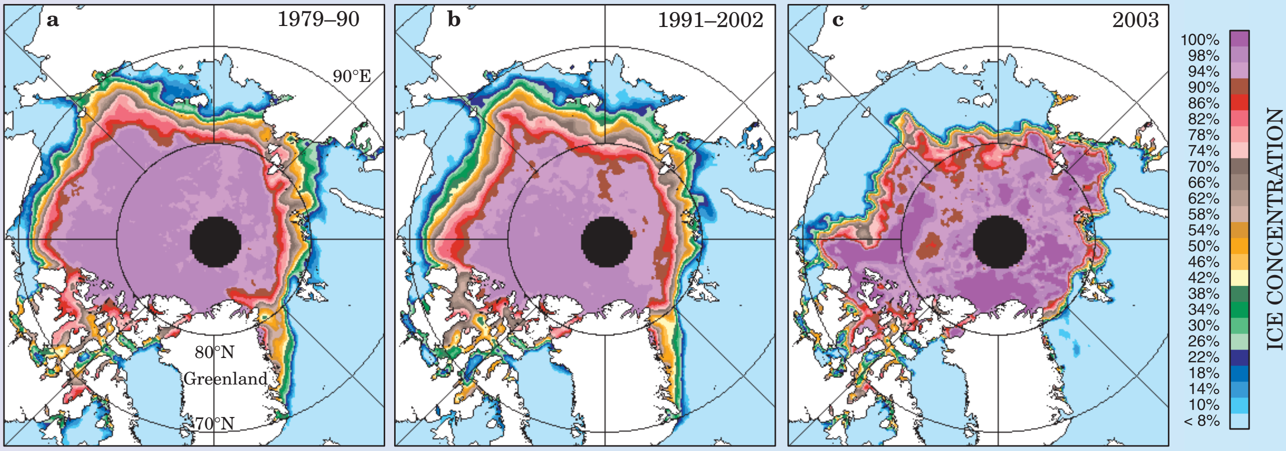


Figure 4. (a) Glaciers on Ellesmere Island and icebergs in Dobbin Bay imaged by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on 31 July 2000. **(b)** Yearly fluctuations in permafrost temperatures at three sampling depths in Fairbanks, Alaska. (Image courtesy of the University of Alberta, NASA's Goddard Space Flight Center, the US/Japan ASTER Science Team, and the Japan Aerospace Exploration Agency. Permafrost data courtesy of V. Romanosky, University of Alaska, Fairbanks.)



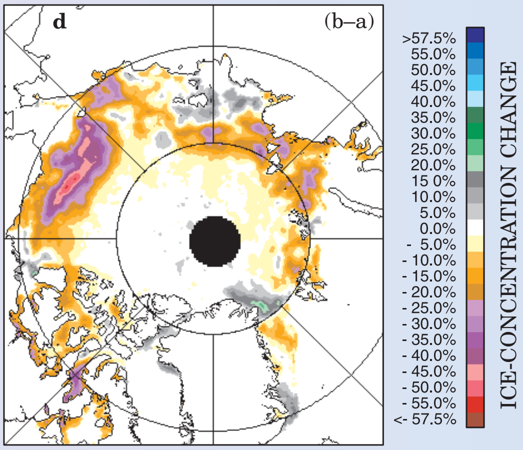


Figure 5. Ice concentrations at their minimum summertime levels were recorded over a 24-year span. Panels a and b display the average minima recorded during the years 1979–90 and 1991–2002, respectively. Panel c shows the minimum concentration recorded in 2003. The ice-concentration boundaries are sharper in this panel because averaging blurs movement. Ice concentrations are measurable down to 8%, below which it is impossible to discriminate between open water and ice-covered areas. Panel d, the difference between the first two panels (b − a), reveals the changes between the two periods. The average size of the ice pack in 1979–90 is greater than that in 1991–2002 by about 12%. The Beaufort Sea, which is north of Alaska, has suffered the most substantial reduction in ice. (Data for images updated from ref. 15.)

atmospheric conditions, including nonprecipitating cloud cover, and under darkness. Researchers estimate the snow thickness by analyzing how the emitted radiation, which mainly originates from the ground, is attenuated by snow. The thicker the snow, the weaker the signal registered by the satellite. But microwave-based data suffer from certain disadvantages: Spatial resolution is coarse, and generally the snow cover must be dry and at least about 5 centimeters thick to produce good measurements. Because the visible monitoring can register snow of thickness as low as about 2 cm—by distinguishing the difference in reflectivity of ground and snow—the extent of snow cover can be estimated more reliably under clear sky conditions. Microwave-based data underestimate the coverage, especially during fall and early winter, when a considerable area is likely to have shallow snow.[11]

For the Northern Hemisphere as a whole, over the period from late 1978 to the end of 1999, both the visible and passive microwave data showed a decrease in snow cover. But the visible data revealed snow cover to be decreasing at a rate of 59 000 km^2 per year (2.6% per decade), whereas the passive microwave data estimated the trend at roughly half that rate.[11] The percentage change is not large, but in the locations where the trend is occurring, the implications could be significant—for example, for freshwater supplies during the melt season and for the ski industry during the winter.

During the past decade, evidence has mounted to indicate that the areal extent of permafrost in the Arctic has similarly decreased, as would be expected under long-term warming conditions.[12] A key concern centers on what that finding might mean for the carbon budget, because permafrost is a carbon reservoir that locks away carbon for thousands of years. The United Nations Environment Programme (UNEP) estimates that 14% of the world's carbon is stored in the arid lands of the Arctic. The release of carbon dioxide and other greenhouse gases, such as methane, through the thawing of the permafrost could further exacerbate the effect of greenhouse warming.[12] Other impacts of the thawing of Arctic permafrost are apparent in the damaged roads, buildings, pipelines, and other infrastructure in Alaska and Siberia. Illustrative of how such damage has affected local economies, about 4% of Alaska's state budget is now being allocated annually to repair such infrastructure.

Figure 4b shows the changes in soil temperature at a permafrost site in Fairbanks, Alaska, at different depths during the past 50 years. The temperature at 0.12 m under the surface fluctuates more than those at 0.52 m and 1.01 m, but all three plots exhibit coherent patterns and a similar average temperature increase. Such yearly correspondence of subsurface-to-surface temperatures is significant and points to a need to continue measurements, this time using satellite data so that scientists may better assess the spatial extent of permafrost changes, especially permafrost decay due to warming.

Satellite images indicate that as the tundra and overlying air have warmed, the tree line in the Northern Hemisphere has moved north into the Arctic. Judging from various resources, including visible and near-IR satellite data and the Normalized Difference Vegetation Index, about 15% of the Arctic tundra has been lost since the 1970s—an amount of land roughly three times the size of California.

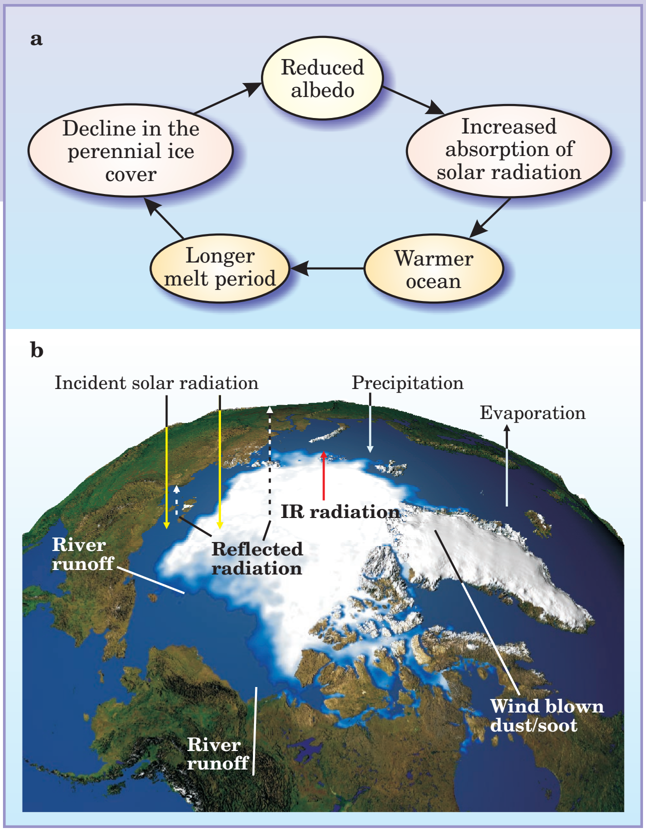


Figure 6. Arctic ice, ocean, and atmosphere are closely interconnected: a change to one influences the others. **(a)** One possible feedback loop. **(b)** Some of the key fluxes that affect the Arctic system. The arrows overlay a satellite-derived map of the perennial ice cover when that cover was least extensive in 2002.

Diminishing sea ice

Researchers use sea-ice concentration maps to estimate the area and extent (that is, the integrated ocean area within at least 15% ice coverage) to which sea ice blankets the Arctic. Those data, in turn, are used to calculate trends. Microwave satellite data indicate that the extent of sea-ice coverage and area covered by sea ice in the Northern Hemisphere as a whole declined at an average rate of 2–3% per decade from 1978 through 2003—about 350 000 km^2 per decade, which is consistent with earlier studies.[13] Sea-ice thickness has also decreased, as revealed by submarine sonar data taken since the 1950s (although those data were collected sporadically and over limited areas) and by satellite altimeter readings taken since the late 1990s.[14] The diminishing sea-ice cover is raising concerns among researchers and others because positive feedbacks with other elements of the climate system may exacerbate the trend and because the sea-ice diminution impacts the Arctic ecosystems, including polar bears and also plants and animals lower on the food chain.

The sea ice extent varies from about 7 to 16 million km^2 from summer to winter. An analysis of the Arctic perennial ice cover—the ice that survives the summer melt—shows particularly dramatic changes. By monitoring the ice minimum each September, researchers have noticed that the rapid decline in perennial ice observed from 1978 to 2000[15] has continued, with the least extensive coverage observed by satellite in 2002 and almost as low an amount in 2003. Figure 5 illustrates the details. Trend analysis using linear regression on the 25 years of data shows that the decline in the perennial ice cover is $9.2 \pm 1.7\%$ per decade. That result is especially important because the perennial ice consists mainly of the thick multiyear ice floes that are the mainstay of the Arctic sea-ice cover. Replacing those thick ice floes with thinner younger ice decreases the average thickness. In a separate study using winter data from 1978–98, researchers found that the wintertime multiyear ice cover had declined by 7% per decade.[15]

The liquid portion of the Arctic Ocean has also changed significantly. Changes in the sea-surface temperature, for instance, can be used to infer the presence of subsurface phenomena such as eddies and deep ocean convection. In the 1990s, the boundary between eastern and western halocline waters shifted away from the Atlantic Ocean, approximately moving from along the Lomonosov Ridge to the Mendeleyev and Alpha Ridges; the result is an increase in Atlantic-type water mass in the eastern Arctic.[16] Such an oceanic shift likely influenced large-scale changes in sea-ice drift patterns, including an eastward deflection of the Transpolar Drift, an average drift pattern that transports ice from the Russian side of the Arctic across the central Arctic basin through Fram Strait and into the Greenland Sea. Recent field programs and ocean buoy deployments also suggest that the salinity of the upper mixed layer is about 10% less than it was in 1976, when similar measurements were taken. That freshening of the Arctic Ocean may be due in part to the thinning of the sea-ice cover and in part to increases in river runoff from greater precipitation and melting of the permafrost. Furthermore, the infrequency of deep convection in the Greenland Sea since the early 1990s and of the Odden ice tongue since 1997 suggest that alterations may be occurring in the regional and perhaps global thermohaline circulation as well.

Feedback

The changes that occur in the Arctic depend substantially on interactions among the atmosphere, ice, ocean, and land. Some of the interactions can be examined through various feedback loops,[17] such as the ice-albedo-ocean feedback pictured schematically in figure 6. A retreat in the ice cover decreases the fraction of light reflected toward space, which increases the solar flux into the ocean, warming its waters and, hence, further thinning the ice and hastening its retreat. A warmer Arctic would also increase surface melt, creating extensive pond waters with a concomitant decrease in surface albedo.

A related loop has a warmer Arctic causing more stormy weather, resulting in increased advection of atmospheric dust particles into the Arctic and a consequent decrease in albedo. As ice retreats, the curl of the wind stress over the ocean increases and causes stronger oceanic gyre circulation and perhaps increased oceanic heat transport into the Arctic. Moreover, as the Arctic warms, the length of the melt period increases, which in turn thins the ice and further hastens its retreat.

Some feedback loops, however, work in the opposite direction. For example, a warmer Arctic would create more evaporation, which in turn could generate more precipitation with a possible increase in snow cover and thus a cooling effect. In addition, clouds tend to shield Earth's surface from solar radiation and thus contribute to additional cooling. On the other hand, clouds also trap long-wavelength radiation from the surface, further warming the atmosphere.

Refining predictions

Although the longest satellite data sets span only about 25–30 years, the findings have revealed much about changes in the Arctic. We now realize that many of the reported changes are not just local but pan-Arctic phenomena. Satellite data have confirmed local changes found from in situ data and have placed them in a larger spatial context, establishing which are (and which are not) typical of the broader picture.

The information derived from the satellite data will be enhanced even further as we incorporate those data into numerical climate models and use them in predictive and explanatory simulations. The data and models together can contribute to a clearer physical understanding of the climate system, help separate the net effects of various feedback loops, extrapolate to the future, and provide a more accurate assessment of the near-term effects of different environmental influences on the Arctic. The observed changes are probably tied to a variety of factors, including greenhouse warming, a changing Sun, and natural climate variability. In time, as the satellite record lengthens, it should become increasingly possible to distinguish cyclical patterns from long-term trends and to separate human from natural influences.

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