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.

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-

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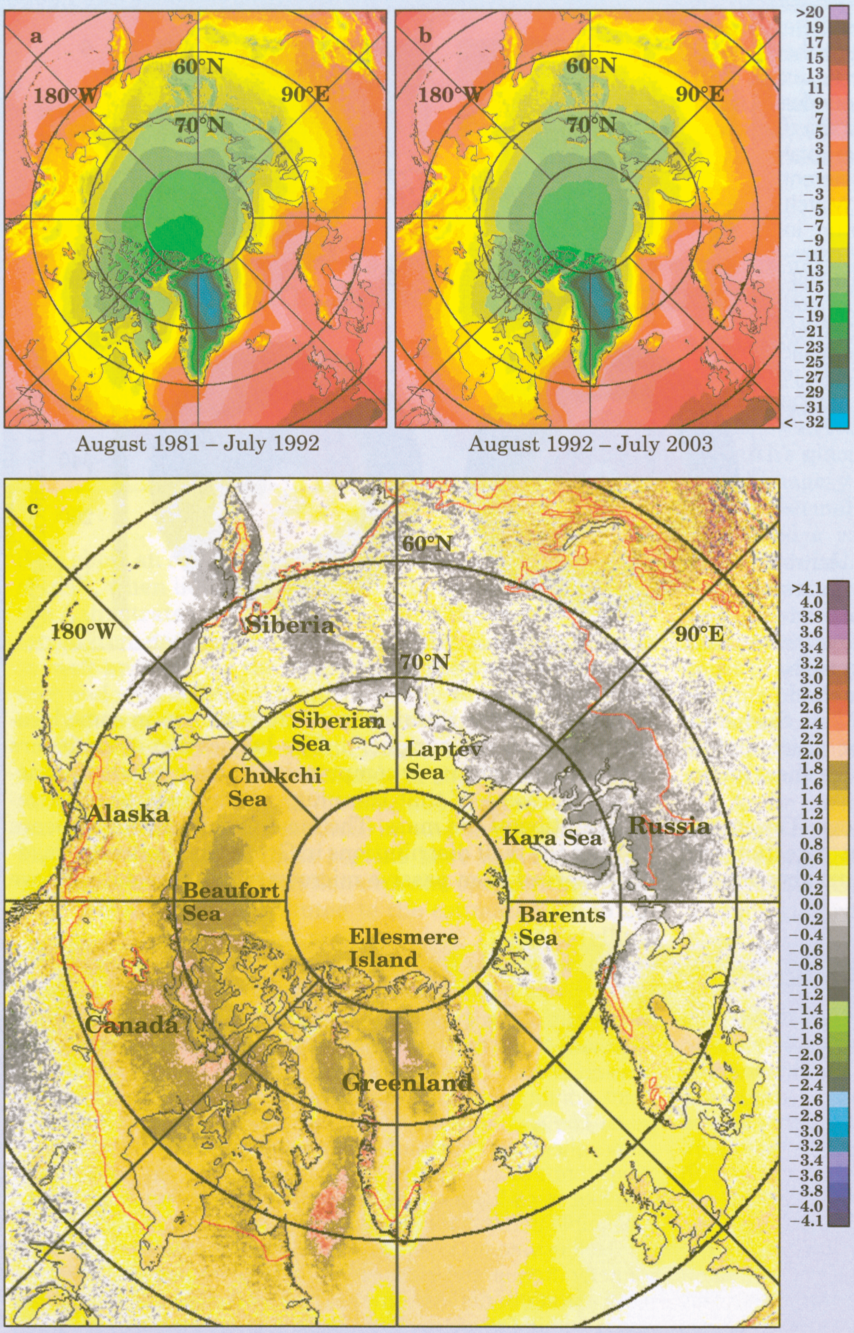

Figure 1. Surface warming is evident from 22 years of IR data collected using the National Oceanic and Atmospheric Administration's series of polar-orbiting satellites: **(a)** average surface temperature from readings taken between August 1981 and July 1992 and **(b)** average surface temperature from 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.