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Arctic warming signals from satellite observations

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Global warming signals are expected to be amplified in the Arctic primarily because of ice-albedo feedback associated with the high reflectivity of ice and snow that blankets much of the region. The advent of satellite remote sensing systems since the 1960s has enabled the acquisition of synoptic data that depict in detail the temporal changes of many Arctic surface parameters. These include surface temperature, sea-ice concentration, snow-cover, surface albedo and phytoplankton concentration. Associated atmospheric parameters, such as cloud cover, temperature profile, ozone concentration and aerosols have also been derived from space-based systems.

Recent observational and phenomenological studies have revealed progressively changing conditions in the Arctic during the last few decades (e.g. Walsh *et al.* 1996; Serreze *et al.* 2000; Comiso and Parkinson 2004). The changes include reductions in the extent and area of surfaces covered by sea-ice and snow, increases in melt area over the Greenland ice sheet, thawing of the permafrost, warming in the troposphere, and retreat of the glaciers. These observations are consistent with the observed global warming associated with the increasing concentration of greenhouse gases in the atmosphere (Karl and Trenberth 2003) and confirmed by modelling studies (Holland and Bitz 2003). The Arctic system, however, is still not well understood, complicated by a fluctuating wind circulation and atmospheric conditions (Proshutinsky and Johnson 1997) and controlled by what is now known as the Arctic Oscillation (AO) which provides a measure of the strength of atmospheric activities in the region (Thompson and Wallace 1998). Meanwhile, the observed Arctic conditions since the 1970s have been shown to exhibit a linear trend that directly contradicts what has been expected from the AO (Overland 2005). The 1990s has been regarded as the warmest decade in the last century and current data indicate that the 2000s may be even warmer, further supporting the linear trend. In this paper, we use satellite data to gain insights into the warming observed in the Arctic and how the abnormally warm conditions during the last few years are evident in the region.

Surface temperature trends

Among the most important parameters used for monitoring climate change is surface temperature. Historically, surface temperature has been recorded primarily in meteorological stations that have been installed all over the world since the middle of the nineteenth century. In the Arctic, however, there is a general paucity in the number of stations, largely because of extreme logistical difficulties and the enormous expense of establishing and maintaining such stations. For a more comprehensive coverage of the region, the most practical alternative is through the use of thermal infrared data provided since 1981 by the Advanced Very High Resolution Infrared Radiometer (AVHRR), as discussed in Comiso (2003). It is fortuitous that surface temperature can be conveniently derived in these polar regions since the infrared emmisivities of polar surfaces, including those of snow, ice, and water, are spatially uniform and close to unity. Atmospheric effects on the signal are also minimal because the region has a low atmospheric water content. Nevertheless, the use of the data is not without problems. First, it should be noted that infrared data provide good surface measurements only during clear sky conditions and therefore, observations over different locations are not uniform in space and time. This effect is minimized partly by the relatively high frequency of observations at high latitudes. Secondly, unambiguous discrimination between cloud-covered areas and snow (or ice) is often difficult. Special cloud masking techniques have to be applied to minimize associated errors as discussed in Comiso (2003). Thirdly, each AVHRR/infrared satellite sensor has a relatively short lifetime of about five years and data from several of these sensors, launched during different time periods, are needed to generate a relatively long time-series. We use in situ data to check the consistency of the radiances from the different AVHRR satellite sensors and to improve the calibration of each sensor.

The general spatial distribution of isotherms in the Arctic region can be inferred from the colour-coded map in Fig. 1(a). This map represents the average of the monthly AVHRR surface temperatures from August 1981 to July 2005 and is referred to as the satellite climatology of the Arctic. The image provides a convenient means of identifying regions of interest, including locations of extremely low temperatures in Greenland, Northern Canada, Siberia and the Arctic basin. The basic monthly images (not shown), which are gridded at a resolution of 6.25×6.25 km, are coherent with each other and reflect the expected changes from one season to another. For a quick general assessment of how the Arctic surface temperature has been changing from one time period to another, the average value of each data element for the first half of the time-series (August 1981 to July 1993) is subtracted from the corresponding average for the second half (August 1993 to July 2005) and the results are shown in Fig. 1(b). This map, which has been renormalized to reflect decadal change, shows a predominance of positive values in the Western Arctic (i.e. Beaufort Sea region and vicinity), North America, Greenland and much of Europe. Surprisingly, there are considerable areas of negative changes, generally in Russia.

For a more rigorous statistical approach, linear regressions were carried out on the temporal variation of temperature in each data element, using monthly temperature anomaly data from 1981 to 2005. The slopes of the regression lines were then used to generate a trend map (Fig. 1(c)), assuming linear dependence. The patterns in this trend map are similar to, but more well-defined, than those in the difference map with the positive (and negative) trends in the same general areas where the positive (and negative) differences are located. The areas of negative and positive trends have been compared with those from in situ data

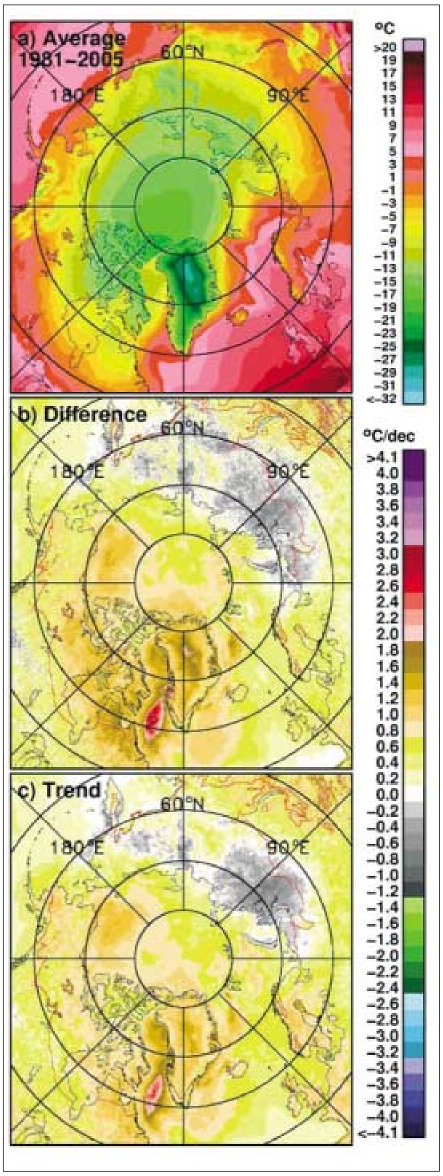

Fig. 1. (a) Average surface temperatures in the Arctic derived from AVHRR from August 1981 to July 2005; (b) difference of the average surface temperature from August 1981 to July 1993 to that from August 1993 to July 2005; and (c) trends in surface temperature from August 1981 to July 2005. The red line in (b) and (c) represents the southern boundary of the discontinuous permafrost while the difference in (b) has been normalized to reflect decadal change.

(Comiso 2003) at locations where the latter are available and the results show good agreement. The overall trend of data inside 60°N is 0.72 ± 0.10 degC per decade, while regionally, the trends are 0.54 ± 0.11 degC per decade over sea-ice, 1.19 ± 0.20 degC per decade over Greenland, 0.84 ± 0.18 degC per decade over North America and 0.13 ± 0.16 degC per decade over Northern Eurasia. It is apparent that significant warming has been occurring in the Arctic but not uniformly from one region to another. Seasonal trends using the same dataset are varied and provide additional insights into the phenomenon as discussed by Serreze and Francis (this issue, pp. 65–69).

To illustrate how the earlier years compare with the more recent years, yearly anomalies in 1982 to 1985 are presented with corresponding anomalies in 2002 to 2005 (Fig. 2). The yearly data are averages from August of one year to July of the following year and hence identify the yearly ice seasons. It is apparent that negative anomalies are a lot more prevalent in the 1980s compared to the 2000s. The aforementioned negative trend in the Russian region at about 90°E (Fig. 1(c)) is probably caused by the positive anomalies in the region in the 1980s. The anomaly maps show large spatial and interannual changes, demonstrating overall warming but at the same time a very complex Arctic system.

Strong signals from the perennial sea-ice cover

The most remarkable warming signal in the Arctic to date as observed using satellite data is arguably the rapidly declining perennial sea-ice cover, as reported previously (Comiso 2002). The relatively long time-series of sea-ice cover data used in this study and in the climatology were derived from data provided by the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the DMSP/Specially Scanning Microwave Radiometer (SSM/I). Since that report, we have had four consecutive years (2002 to 2005) when the extent and area of the Arctic perennial ice cover were abnormally low (Fig. 3).

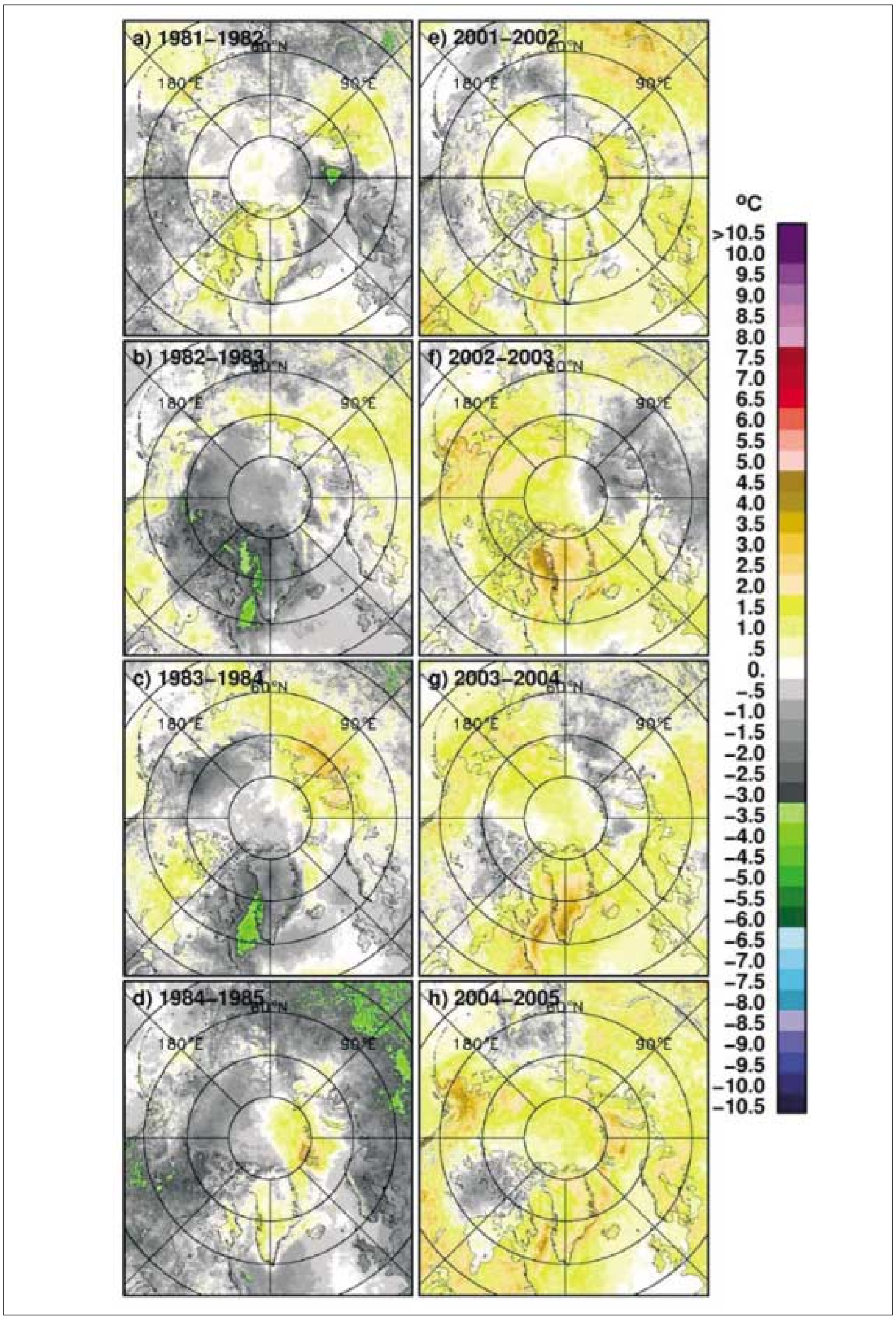

Fig. 2 Yearly temperature anomaly maps in (a) 1981–82; (b) 1982–83; (c) 1983–84; (d) 1984–85; (e) 2001–02; (f) 2002–03; (g) 2003–04; and (h) 2004–05. Yearly averages are from August of one year to July the following year.