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Title: Satellite Observed Changes in the Arctic

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Abstract:

The Arctic is currently considered an area in transformation. Glaciers have been retreating, permafrost has been diminishing, snow covered areas have been decreasing, and sea ice and ice sheets have been thinning. This paper provides an overview of the unique role that satellite sensors have contributed in the detection of changes in the Arctic and demonstrates that many of the changes are not just local but a pan-Arctic phenomenon. Changes from the upper atmosphere to the surface are discussed and it is apparent that the magnitude of the trends tends to vary from region to region and from season to season. Previous reports of a warming Arctic and a retreating perennial ice cover have also been updated, and results show that changes are ongoing. Feedback effects that can lead to amplification of the signals and the role of satellite data in enhancing global circulation models are also discussed.

Popular Science Summary

The Arctic plays important roles in the Earth's climate system, for instance as an energy sink, and it is considered by some to be likely to provide an early signal of climate change, because of feedbacks associated with the high albedo (reflectivity) of the snow and ice that blanket much of the region. In an era when anthropogenic global warming has been a contentious issue, studies of the Arctic and observed changes in the region gain added importance, and indeed substantial changes in the Arctic and vicinity have been reported in the last several years. Glaciers have retreated, permafrost has diminished, snow covered areas have decreased, and sea ice and ice sheets have thinned. The reports indicate in concert that substantial physical changes have taken place. This paper provides an overview of the unique role that satellite sensors have contributed in the detection of changes in the Arctic and demonstrates that changes are not just local but a pan-Arctic phenomenon. Changes from the upper atmosphere to the surface are discussed and it is apparent that the magnitude of the trends tends to vary from region to region and from season to season. Previous reports of a warming Arctic and a retreating perennial ice cover have also been updated, and results indicate that changes are continuing.

Significant Findings:

Although the longest satellite data sets are only about 25-30 years long, much has been learned about global change through their utilization, and we now realize that many of the reported changes in the Arctic are not just local but pan-Arctic phenomena. Changes appear to be occurring throughout the Arctic environment, from the upper atmosphere to deep ocean circulation and subsurface permafrost. Large changes in surface and tropospheric temperatures, melt areas in Greenland, snow, glaciers, permafrost, and the perennial sea ice cover have been observed from the 1980s to the early 21st century. Analysis of the impacts that the observed changes could have on the radiative energy fluxes between the ice, ocean, and atmosphere suggests that an acceleration of the changes could occur.

Satellite Observed Changes in the Arctic

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Introduction

One of the most inaccessible and inhospitable areas on the surface of the globe is the Arctic region. It is inaccessible because the Arctic Ocean, which is its central component, is covered mainly by sea ice, about 3 m thick on average. It is inhospitable because of extremely cold and adverse weather conditions. The Arctic Ocean spans an area of 14 million square km^2 and is surrounded by Russia and Europe in the east and Alaska, Canada, and Greenland in the west. The Chukchi Sea of the western Arctic is connected to the Bering Sea through a small opening that provides a link to the Pacific Ocean, but the major connections to the rest of the world's oceans are to the Atlantic through Fram Strait and the Barents Sea.

The Arctic plays important roles in the Earth's climate system, for instance as an energy sink, and it is expected to provide an early signal of climate change because of feedbacks associated with the high albedo (reflectivity) of the snow and ice that blanket much of the region. In an era when anthropogenic global warming has been a contentious issue, studies of the Arctic and observed changes in the region become increasingly important, and indeed substantial changes in the Arctic and vicinity have been reported in the last several years. Glaciers have been retreating, areas of permafrost have been diminishing, snow covered areas have been decreasing, and sea ice and ice sheets have been thinning. The reports indicate in concert that physical changes in the region are taking place. However, some of them are based on few and sparsely distributed measurements hardly considered representative of the pan Arctic system. This is understandable because of the harsh nature of the environment that makes it difficult to set up and maintain scientific stations. There were no means of readily obtaining measurements for the full Arctic until the development of satellite remote sensing systems. Although the first satellites were launched in the late 1950s, it wasn't until the 1970s that multi-channel sensors enabling accurate measurements of Arctic surface parameters were introduced. The satellite observations provide the means to study the entire region from a global perspective, revealing intriguing anomalies and trends.

Surface warming

Among the most critical parameters for studies of changes in the Arctic environment is surface temperature. This is especially the case in regions where the temperatures are near the freezing point, since in such regions, slight fluctuations can make a major difference in whether ice and snow covers increase or melt away. A change of a few days in the onset of melt and/or freeze-up could mean significant changes in the areal extent of snow and sea ice.

With thermal infrared radiometers on board satellite systems, we are now able to investigate spatial as well as temporal variability of surface temperatures during clear sky conditions in the pan Arctic region. Monthly time series of surface temperature data in the Arctic have been generated for the period August 1981 through the present using NOAA/Advanced Very High Resolution Radiometer (AVHRR) data. To illustrate how such data can be used for change detection, Figure 1a presents the change in surface temperature from the first eleven to the second eleven years of operation of the sensor. The map is the difference of average temperatures over the period from August 1981 to July 1992 (Figure 1b) and average temperatures from August 1992 to July 2003 (Figure 1c). The difference map shows that the latter decade was warmer than the previous one in practically all areas of the Arctic except parts of Russia. It also shows that the amount of warming differs from one region to another and is generally consistent with trends reported previously for a shorter time period[1]. Simple regression analysis reveals that from 1981 to 2003 surface temperatures have been increasing at the average rate of 0.55 $\pm$ 0.14 K/decade over sea ice, 0.79 $\pm$ 0.22 K/decade over Greenland, -0.15 $\pm$ 0.18 K/decade over Eurasia, and 0.76 $\pm$ 0.19 K/decade over North America. The trends also vary considerably with season, with the spring, summer and fall showing warming in practically all locations but with winter showing a predominance of cooling, especially in the Russian region. For summer, the trend over sea ice is relatively high, at about 1.2 K per decade. A lengthening of the melt season by 9 to 17 days per decade, depending on region, is also revealed, affecting the sea ice cover, Greenland ice sheet, glaciers, permafrost, and snow cover.

Spring Warming in the Troposphere

Changes in tropospheric temperature in the Arctic have been studied using TIROS Operational Vertical Sounder (TOVS) data in combination with the National Center for Environmental Prediction (NCEP)-NCAR reanalysis data set[2]. The TOVS data were used mainly for characterizing horizontal variations and gradients in temperature for different time periods from 1979 to 1998 while the NCEP-NCAR data were used for time series/temporal variability studies. This scheme was used because of uncertainties in the calibration of TOVS and the lack of adequate data in the Arctic to check its temporal consistency. Interannual changes are observed to be large, as illustrated in Figures 2a and 2b, which show large negative monthly temperature anomalies in March 1990 and large positive anomalies in March 1998, respectively, at 200 hPa. 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. This is consistent with surface temperature data as described in the previous section.

Stratospheric ozone and cooling

Ozone in the stratosphere is known to be an important protector of life on Earth because of its absorption of ultraviolet radiation from the sun. This absorption in turn is the basis of the use of satellite ultraviolet radiometers for detecting ozone from space. The Total Ozone Mapping Spectrometer (TOMS) in particular has provided a record of atmospheric ozone since the launch of the first TOMS instrument on the Nimbus 7 satellite in 1978 (e.g., Figures 2c and 2d). The decay of stratospheric ozone is a complicated chemical process generally aided by cold stratospheric temperatures and the concomitant formation of polar stratospheric clouds. It is highly variable from year to year, dependent in large part on the chemical and temperature conditions and the planetary wave forcing affecting them[3]. Overall, the Arctic stratosphere has become colder in recent decades, promoting the destruction of stratospheric ozone, which in turn leads to further stratospheric cooling because of lessened absorption of ultraviolet radiation. Arctic total column ozone data from TOMS and the European Remote Sensing Satellite Global Ozone Monitoring Experiment (GOME) over the period November 1978 – December 2000 show negative trends in February, March, and April and no statistically significant trends in the other nine months. The trends are largest in March, at about 1%/year, versus approximately 2.4%/year decreases in the Antarctic in October, generally the peak month for the Antarctic ozone hole[4]. Although, as a result of the 1987 Montreal Protocol and subsequent international agreements, ozone-depleting chemicals are no longer increasing in the stratosphere, ozone could continue to decrease if the stratosphere, as expected, continues to cool.

Melt and thinning in the Greenland Ice Sheet

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 percent of the island of Greenland. An additional 3 percent is covered by smaller glaciers and ice caps. The Greenland ice sheet is on average 1.7 km thick, with a total volume of ice that, if entirely melted, would cause an increase of about 7.2 meters in global sea level. Such a catastrophe is not imminent, but the volume of ice and its relevance to sea level make the monitoring of the ice sheet an important priority. The temperature difference map in Figure 1a indicates warming over most of the ice sheet. Over the last decade, regular flights over the ice sheet with a NASA P3 aircraft equipped with a lidar ranging system have indicated that around the periphery, the ice sheet has thinned by as much as 1 m in some locations[5]. This has been reported to be in part due to dynamics at the grounding line that leads to some redistribution of the mass[6]. The most visible change in Greenland as observed by satellites is the change in melt distributions, with significant expansion of the melt region from 1992 to 2002[7] (Figure 3). In this case, passive microwave data are used, because they show an enhanced surface signature during onset of melt, when liquid starts forming in the snow cover. A dramatic increase of 17% in the melt area over the 10-year period is detected. Such an increase in melt area affects the character of the snow on the surface and subsurface and may have been in part responsible for the observed ice sheet thinning.

Receding mountain glaciers

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 these regions have participated in what appears to be an overall global decrease in mountain glaciation over the past century[8], a decrease that has contributed to the estimated 10-20 cm sea level rise since 1900[9]. Satellites can monitor these glaciers, although in general, glacier processes tend to operate on longer time scales than those in the atmosphere and upper oceans, so that the satellite record has been useful more for obtaining a baseline picture of glacial extent as of the late 20th and early 21st centuries than for determining long-term trends. Landsat imagery in particular has been used for a multivolume *Satellite Image Atlas of Glaciers of the World*[8], with the European and North American volumes both including Arctic areas. These volumes provide a baseline of global land glaciation as of the 1970s and 1980s. They are being followed by an international program using data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board the Terra satellite, launched in December 1999, to map the extent of and changes in glaciers around the Earth. In Alaska alone, 15,000 glaciers are being monitored, most of which appear to be retreating. ASTER obtains high resolution (15-90 m) imagery from 14 channels at wavelengths from visible to thermal infrared. The Landsat and ASTER data confirm a variety of changes in Arctic glaciers, with some glaciers growing, some decreasing, some oscillating, and some remaining fairly steady, although overall the trend has been toward reduced glacier coverage. Figure 4 provides a sample ASTER image, showing several glaciers on Ellesmere Island and icebergs calved into Dobbin Bay from the Eugenie Glacier's floating tongue. Calving of icebergs is a primary mechanism of glacier change.

Among the most dramatic of the glacial ice changes in the Arctic during the period of the satellite record is the major break-up of the sea-based Ward Hunt Ice Shelf along the northern coast of Ellesmere Island over the period 2000-2002. This break-up is well recorded with satellite observations from the RADARSAT synthetic aperture radar. RADARSAT observations show no evidence of fracturing of the shelf in 1998 and 1999, a clear fracture in April 2000, and substantial decay by September 2002[10].

Retreating snow cover

Snow cover over land can be monitored from space with both visible/infrared data and passive-microwave data, although with different strengths and weaknesses and somewhat different results. The passive-microwave data have the advantages of being obtainable under most atmospheric conditions (including non-precipitating cloud covers) and under darkness as well as light; but they have the disadvantages of generally requiring the snow cover to be dry and at least about 5 cm thick for good measurements to be obtained. Because the visible data can register snow of thickness down to about 2 cm, snow extents derived from the passive-microwave data tend to be less than those derived from the visible data, especially during fall and early winter, when a considerable area is likely to have shallow snow between the approximately 2 cm and 5 cm respective limits[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 show negative 21-year trends in snow cover, but the visible data show a trend of -59,000 km^2/yr (2.6%/decade) while the passive-microwave data show a lesser magnitude trend of -35,000 km^2/yr (1.7%/decade)[11].

Permafrost thawing

During the last decade, there has been mounting evidence that the areal extent of permafrost (frozen soil) in the Arctic has been declining, which is what would be expected under long-term warming conditions. A key concern centers on what this might mean for the carbon budget. Permafrost has served as a carbon sink, locking away carbon and other greenhouse gases for thousands of years. It has been estimated by the United Nations Environmental Program (UNEP) that 14% of the world's carbon is stored in the arid lands of the Arctic. The release of this carbon and other greenhouse gases, such as methane, through the thawing of the permafrost would further exacerbate the effect of greenhouse warming. Other impacts of the thawing of Arctic permafrost are being felt as roads, buildings, pipelines and other infrastructure in Alaska and Siberia have been damaged through movements and weakenings of what was once a solid permafrost foundation. Illustrative of how such damage has affected local economies, about 4% of the budget of the state of Alaska is now being allocated annually for repairs to these damaged infrastructures.

To gain insight into the current state of Arctic permafrost, plots of changes in soil temperature at different depths during the last fifty years at a permafrost site in Fairbanks, Alaska are shown in Figure 4b. The temperature at 0.12 m fluctuates more than those at 0.52 m and 1.01 m, but all three measurements are coherent and follow the same pattern of temperature increase[12]. The permafrost is most vulnerable in areas undergoing warming and with temperatures that rise above freezing (see Figure 1).

The current location of the discontinuous permafrost boundary, as reported by UNEP, is indicated by a red line in Figure 1a. Satellite images have revealed that the tree line in the Northern Hemisphere has been moving north into the Arctic as the tundra warms and the air temperature increases. There has been about 15 % loss in the tundra area in the Arctic since the 1970s[13], as the tundra is being replaced by shrubs and trees.

Declining Sea Ice Cover

The longest satellite record of the Arctic sea ice cover comes from passive microwave data, starting in the 1970s. The advent of multichannel passive microwave data in 1978 enabled ice concentrations in the Arctic to be derived with reasonable accuracy and consistency. Sea ice concentration maps are used to estimate the extent (at least 15% ice coverage) and actual area of sea ice, which in turn are used to monitor trends in the sea ice cover. Satellite data from 1978 through 2003 currently show that the extent and area of sea ice in the Northern Hemisphere as a whole have been declining at an average rate of 2 - 3% per decade, consistent with earlier studies[14]. Satellite altimeter data have also indicated decreases in the thickness of the ice cover since the late 1990s [15]. On a longer time scale, a decline in thickness since the late 1950s was reported using submarine data, but the latter are relatively sparse in both temporal and spatial coverage.

Results from analysis of the Arctic perennial ice cover have shown particularly dramatic changes. Perennial ice refers to the thick sea ice cover that survives the summer melt. The amount of perennial ice is estimated by determining the ice area during the summer minimum ice coverage, generally occurring in September. A rapid decline in the perennial ice cover was reported using data from 1978 to 2000[16]. Since then, the least extensive perennial ice cover observed by satellite occurred in 2002, and the following year had almost as low an amount. The average of the first 12 years of multichannel passive microwave ice concentrations (percent areal coverages of ice) during the summer minimum is shown in Figure 5a, and the average for the subsequent 12 years is shown in Figure 5b. Ice concentrations are presented with a cutoff of about 8%, below which it is not possible to discriminate between open water and ice covered areas. At any particular time, the ice edge is generally sharper, as illustrated in Figure 5c, which represents the ice concentration map during ice minimum in 2003. Averaging tends to blur the ice edge because of its substantial yearly movement. The average size of the ice pack in the 1979-1990 period is significantly greater than that of the 1991-2002 period (Figure 5d). The region with substantial reduction in the Beaufort Sea, north of Alaska and the Bering Strait (Figure 5d), has no ice at the summer minimum in 2003 (Figure 5c). Overall, there is a difference of 12 % in area for the two 12-year periods. Trend analysis using linear regression on the 25 years of data shows that the decline in the perennial ice cover is 9.2 % per decade. This result is especially important since the perennial ice cover consists mainly of the thick multiyear ice floes that are the mainstay of the Arctic sea ice cover. Replacement of these thick ice floes with thinner younger ice would involve a decrease in average thickness. The retreat of the perennial ice is strongly correlated with the increase in the surface temperature of summer ice (R=0.83).

Changing liquid Arctic Ocean

The liquid portion of the Arctic Ocean has been observed to be changing significantly as well. In the 1990s, the boundary between eastern and western halocline waters (with and without Pacific influence) has shifted away from the Atlantic from approximately along the Lomonosov Ridge to the Mendeleyev and Alpha ridges, with a resulting increase in Atlantic type water mass in the eastern Arctic[17]. Such an oceanic shift is likely influencing the large scale changes in sea ice drift patterns that include the eastward deflection of the Transpolar Drift. Recent field programs and ocean buoy deployments also suggest that the salinity of the upper mixed layer is about 10% less than in 1976, when similar measurements were taken, suggesting a freshening of the Arctic Ocean. This may be due in part to the thinning of the sea ice cover. Furthermore, the absence of deep convection in the Greenland Sea since the early 1990s and the absence of the Odden ice tongue since 1997 suggest alterations in the characteristics of the ocean that may impact the global thermohaline circulation.

Feedbacks in the Arctic System

The changes occurring in the Arctic can be assumed to be highly interconnected, as the Arctic system involves strong coupling among the atmosphere, ice, ocean, and land components. Some of the interactions can be examined through a variety of feedback loops[18], such as the ice-albedo-ocean feedback shown schematically in Figure 6a. A retreat in the ice cover would cause a decrease in surface albedo that in turn would cause an increase in solar flux into the ocean, a warmer ocean, and hence further thinning and retreat of the ice cover. A related loop has a warmer Arctic causing more stormy weather, with increased advection of atmospheric dust particles into the Arctic and a consequent decrease in albedo. A warmer Arctic would also increase surface melt, causing more extensive meltponding, with concomitant decreases in surface albedo. The albedo decreases allow more solar flux absorption and hence continued warming that leads to further retreat in the ice cover. As ice retreats, the curl of the wind stress over the ocean increases, causing stronger oceanic gyre circulation and perhaps increased oceanic heat transport into the Arctic. Also, as the Arctic warms, the length of the melt period increases and this in turn causes a thinning and thus further retreat of the ice cover.

Some feedbacks, however, work in the opposite direction. For example, a warmer Arctic would cause more evaporation, which in turn generates more clouds and more precipitation, with a possible cooling effect. Substantial clouds also tend to shield the surface from solar radiation and hence produce additional cooling. Figure 6b shows some of the key fluxes that are associated with the Arctic system and that contribute to the aforementioned feedbacks. The sea ice cover in the background is derived from passive microwave data and corresponds to the perennial ice cover in 2002, which is the least extensive perennial ice observed during the satellite era.

Summary

Although even the longest satellite data sets are only about 25-30 years in length, much has been learned about global change through their utilization, and we now realize that many of the reported changes in the Arctic are not just local but pan-Arctic phenomena. Changes appear to be occurring throughout the Arctic environment, from the upper atmosphere down to deep ocean circulation and subsurface permafrost. Satellites provide an important tool for detecting changes and revealing their spatial extent. The information obtained will be enhanced even further when the improved data sets provided by satellites are incorporated in numerical climate models. The data and models together can provide a clearer understanding of the physics of the climate system and allow us to extrapolate to the future and at the same time have an accurate assessment of the near term effects of environmental forcings on the Arctic. As the satellite record gets longer, it will also become more possible to distinguish cyclical patterns from long-term trends and to separate human from natural forcings.

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Satellite data and Inversion Techniques

The best platforms for observing changes in the Arctic as a whole are the polar orbiting satellites, the first of which were launched in the 1960s. These satellites, sometimes referred to as "eyes in the sky," have been equipped with a variety of sensors that record data at various frequencies from ultraviolet to visible, infrared, 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 allow synoptic monitoring of the surface at a relatively high temporal resolution (every hour and a half for the highest latitudes, and a few times a day for most regions at lower Arctic latitudes). Utilization of the data requires inversion algorithms that convert radiances or backscatters measured by the satellite into geophysical parameters taking into account atmospheric effects on the radiation and spatial variations in the emissivity and backscatter of the surface. The design of such an inversion technique requires an understanding of the emission characteristics of the surface of interest and how the radiation gets affected by the atmosphere before it reaches the satellite sensor.

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

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

where ε is the emissivity of the surface, T_S is the physical temperature of the surface, $\tau'(z)$ 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 represents radiation directly from the earth's surface, which is often the dominant contribution for measurements at microwave frequencies. The second term represents satellite observed radiation directly from the atmosphere, while the third term represents downwelling radiation from the atmosphere that has been reflected toward the satellite from the earth's surface. A fourth term that takes into account the reflected contribution of radiation from free space, which is a negligible additive contribution and is not included in equation (1).

To illustrate an inversion technique, one parameter that is frequently used in polar studies is sea ice concentration as derived from passive microwave data. For areas within the ice pack, the radiation observed by the passive microwave satellite sensor comes from the ice, open water, or a combination of both. Most simply, when the ice surface is uniform radiometrically, then the observed brightness temperature, T_B, is expressed in terms of the relative contribution from each surface by a linear mixing formulation given by

$$T_B = T_O C_O + T_I C_I \quad (2)$$

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 ocean surface components within the field-of-view of the satellite instrument. C_O and C_I add to unity (i.e., $C_O = 1-C_I$). Equation (2) and its extension to more than one ice type form the basis for sea ice concentration algorithms. The challenge is how to take into account 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 taken into account or at least minimized through the utilization of several passive microwave channels, as described in various reports[1,6,14].

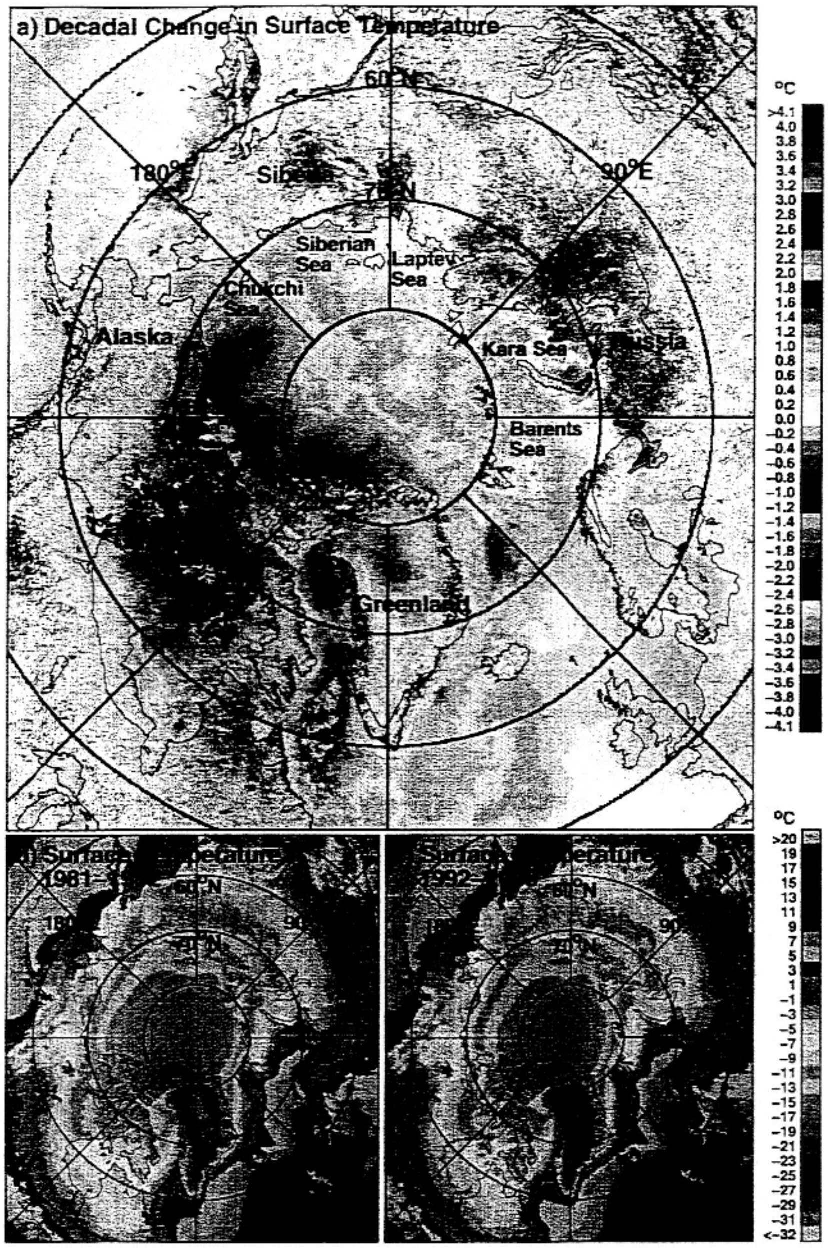

Figure 1. Surface warming signal from 22 years of satellite infrared data from the AVHRR instruments on the NOAA series of satellites: (a) difference map of 11-year temperature averages (c-b); (b) average surface temperature from August 1981 through July 1992; (c) average surface temperature from August 1992 through July 2003. Red line in Fig. 1a represents the southern boundary of the discontinuous permafrost.

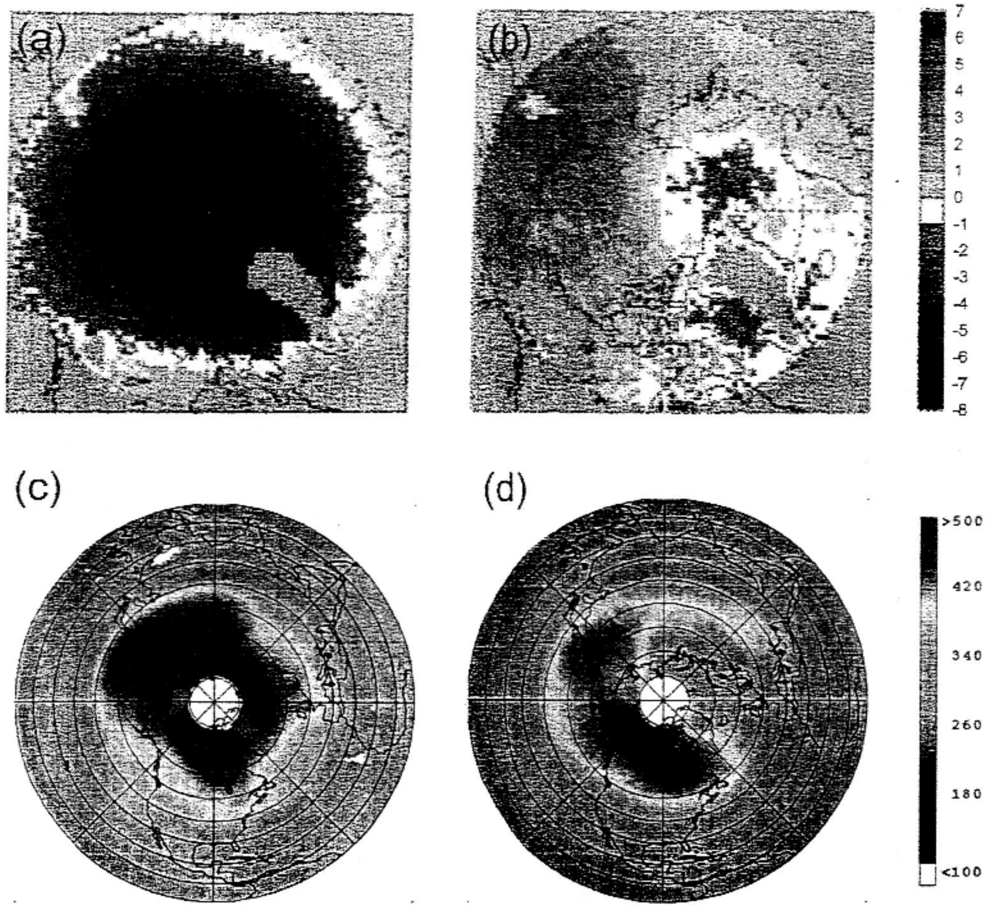

Figure 2. Satellite-derived 200-hPa temperature anomalies in (a) March 1990 and (b) March 1998, and satellite-derived total-column ozone measurements in the Arctic for (c) March 1979 and (d) March 2003, from TOMS.

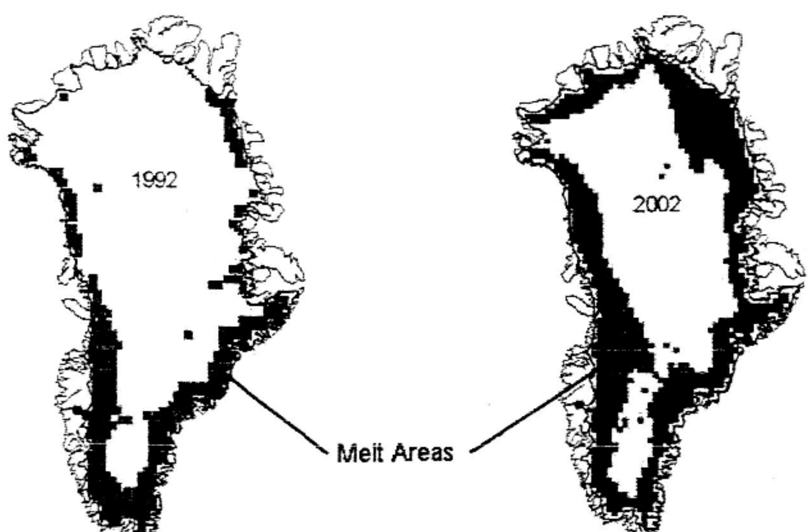

Figure 3. Changes in the area of summertime melt over Greenland from 1992 to 2002. Source: Konrad Steffen and Russell Huff, University of Colorado, Boulder.

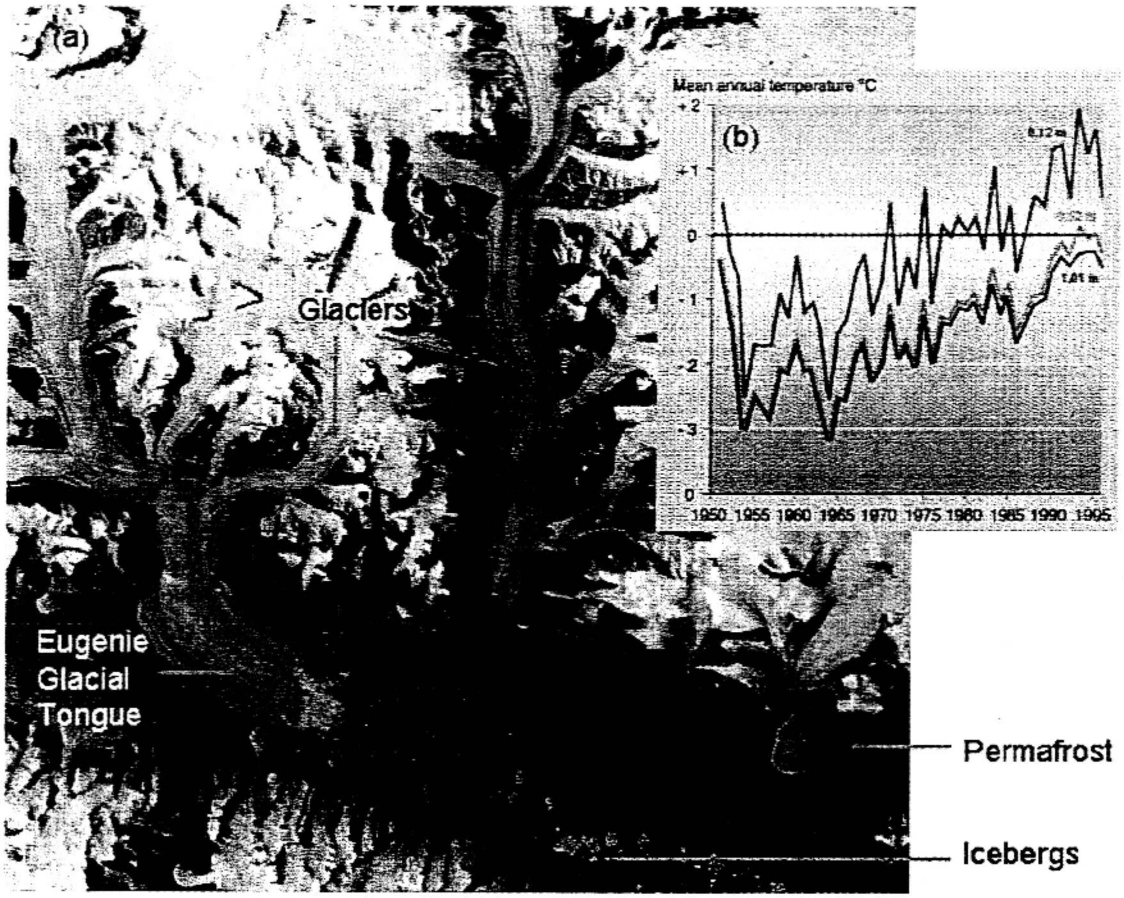

Figure 4. (a) ASTER image of glaciers on Ellesmere Island and icebergs in Dobbin Bay. Image courtesy of the University of Alberta, NASA Goddard Space Flight Center, and the U.S./Japan ASTER Science Team. (b) Changes in the permafrost temperatures (° C) at various depths in Fairbanks (Alaska). Red is for a depth of 0.12 m, yellow a depth of 0.52 m, and blue a depth of 1.01 m. Source: V. Romanosky[12].

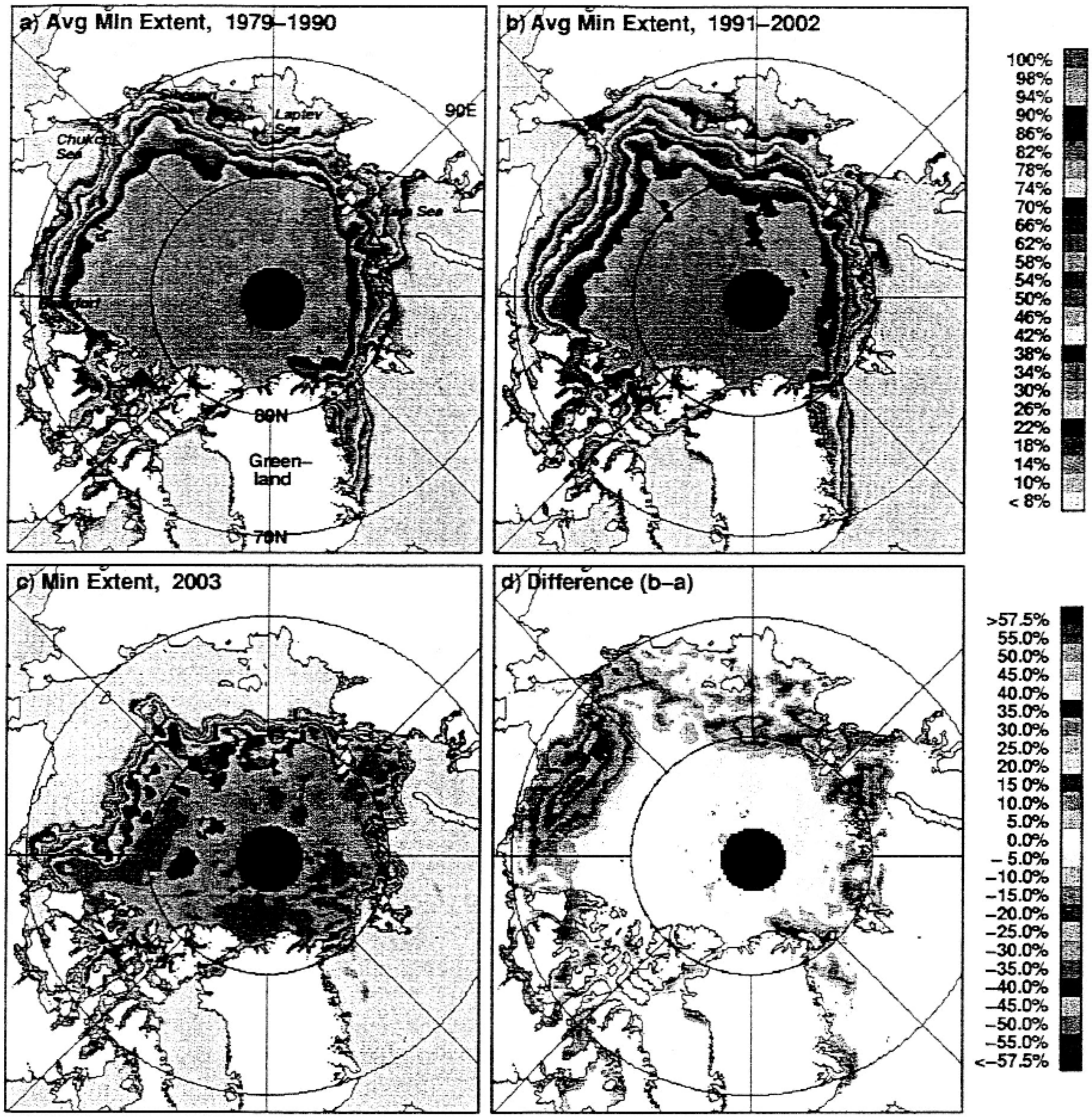

Figure 5. Average ice concentrations at the summer minimum for the years (a) 1979-1990, (b) 1991-2002, and (c) 2003; (d) difference map of the averages in (a) and (b).

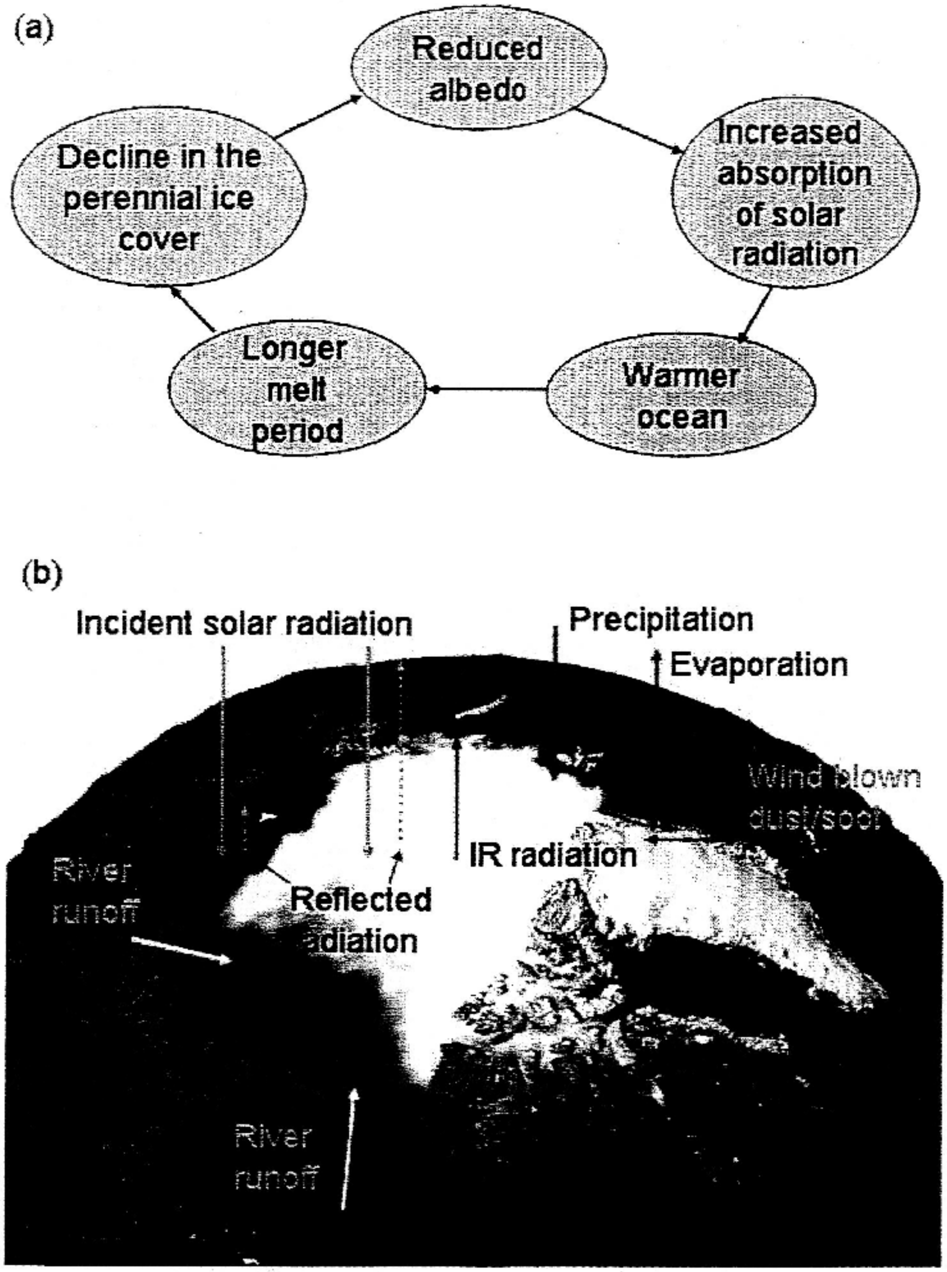

Figure 6. (a) Sample positive feedback loop among sea ice, ocean and atmosphere. (b) Schematic of fluxes that affect the Arctic system, overlain on a satellite-derived ice concentration map of the perennial ice cover when it was least extensive, in 2002.

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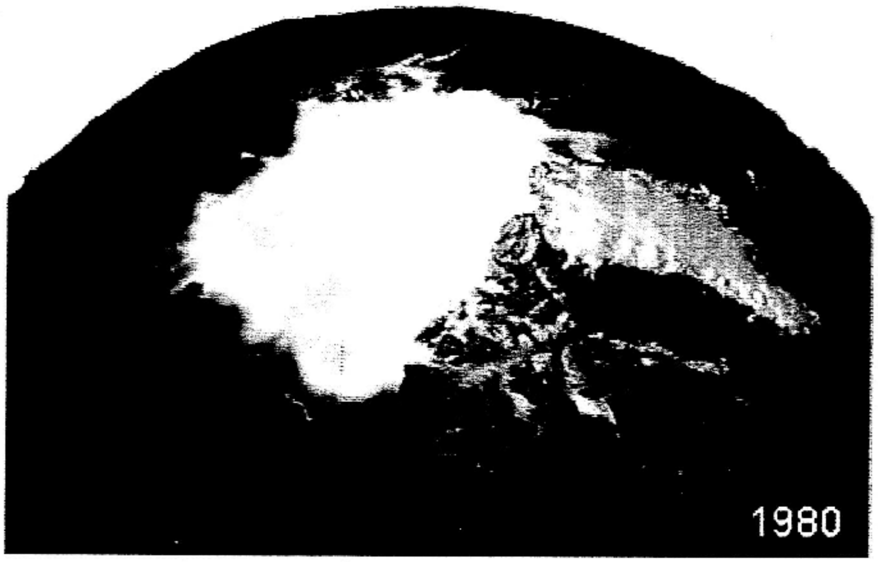
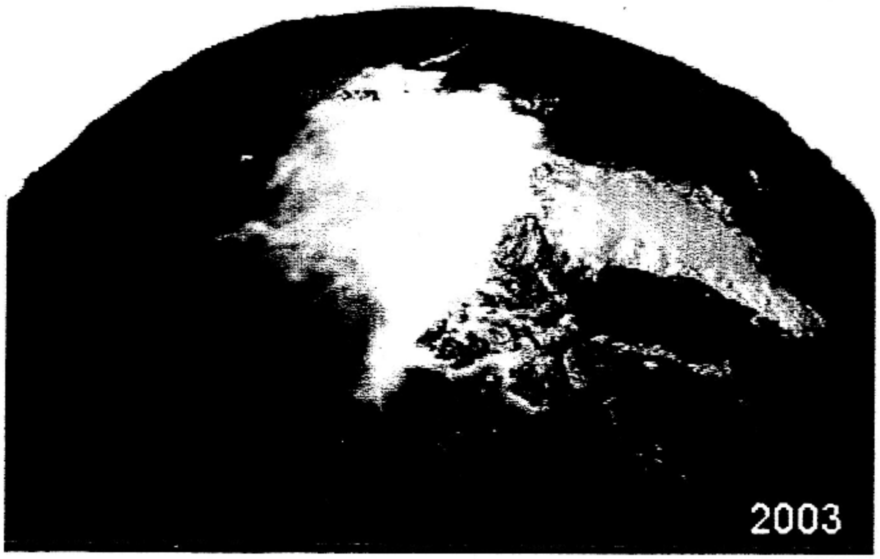
PHYSICS TODAY





Arctic perennial ice on retreat