13.10

RECENT ARCTIC CLIMATE TRENDS OBSERVED FROM SPACE AND THE CLOUD-RADIATION FEEDBACK

Xuanji Wang[1]* and Jeffrey R. Key[2]
[1]Cooperative Institute for Meteorological Satellite Studies University of Wisconsin-Madison Madison, Wisconsin
[2]Office of Research and Applications, NOAA/NESDIS Madison, Wisconsin

1. INTRODUCTION

Numerous climate modeling studies have shown that the Arctic is one of the most sensitive regions to global climate change (Manabe, 1992, 1994; Miller, 2000; Meehl, 1990) as a result of the feedback between surface temperature, surface albedo, and ice extent, known as the ice-albedo feedback (Curry, 1996). This theory has been confirmed by a variety of observational evidence, though records of Arctic climate change are brief and geographically sparse. Recent studies have clearly shown that Northern Hemisphere sea ice extent and thickness have been decreasing beyond the expectation of natural climate variability (Parkinson, 1999; Vinnikov, 1999). Serreze et al. (2000) found that the surface air temperature during 1966-1995 increased markedly over Eurasian and northwest North American land masses with the trends of as high as 0.5^{o}C per decade for some locations, while an increase of Arctic sea ice extent was found in winter. Wallace et al. (Wallace, 1996) point out that the upward tendency in observed Northern Hemisphere temperatures in recent decades is strongly influenced by circulation changes in the cold season.

While these studies generally agree that the Arctic has been warming, it is not clear how the other aspects of the climate system have responded. Have cloud properties changed? If, for example, cloud amount increases, will the cloud-radiation feedback act to modulate the rise in surface temperature? Here we use satellite data to estimate cloud amount, cloud optical depth, cloud particle phase and size, cloud temperature, surface temperature, surface broadband albedo, surface radiation fluxes, and the cloud radiative effect (often termed "cloud forcing"). It will be shown that the Arctic has undergone significant changes in surface temperature, cloud amount, cloud particle phase and size as well as atmospheric precipitable water, but that warm and cold season trends for some parameters are of opposite sign. Additionally, the interaction between the surface and clouds - the cloud-radiation feedback - is such that the surface radiation budget has changed very little over the last two decades.

2. DATA AND RETRIEVAL ALGORITHMS

Data from the Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP) project (Meier, 1997) were used in this study. The APP data of twice-daily composites of visible, near-infrared, and thermal radiances at a 5 km spatial resolution from 1982 to 1999 are subsampled to 25 km. For the analysis of long-term trends, inter-satellite differences must be small. If the calibration is done correctly, differences in brightness temperatures and reflectances between the AVHRRs on two consecutive satellites should only be a function of changes in viewing/illumination geometry for different overpass times, differences in spectral response functions, and changes in the scenes being observed. We have examined the time series of AVHRR brightness temperatures and reflectances for NOAA-7, -9, -11, and -14 over the period of 1982-1999 and found no observable bias or inconsistency. Figure 1 shows the time series of channel 4 brightness temperatures for 1982-1999, a period covering four satellites (NOAA-7, -9, -11, and -14) at Barrow, Alaska. This site was used because it showed no significant trend in surface temperature over the study period

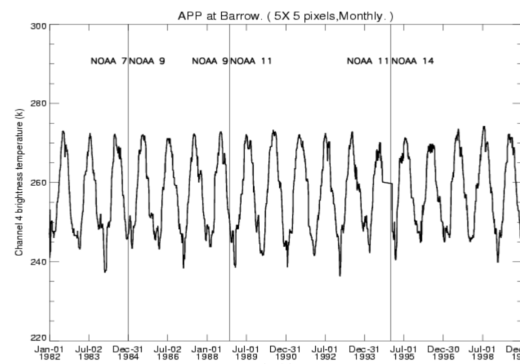

Figure 1. The time series of monthly average AVHRR channel 4 brightness temperatures from January 1, 1982 to December 31, 1999 at Barrow, Alaska for 1400 local solar time. Note: there are no data available from September 14, 1994 to January 18,1995.

We have extended the standard APP product to include all-sky surface temperature, all-sky surface albedo, cloud properties (particle phase, effective radius, optical depth, temperature and pressure), radiative fluxes and cloud forcing (hereafter APP-x). The processing employs the Cloud and Surface Parameter Retrieval (CASPR) system (Key, 2000) with the atmospheric profile data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kistler, 2001) and ozone from the International Satellite Cloud Climatology Project (ISCCP) D2 data set (Rossow, 1996). The daily APP composite data used here are centered on a local solar time (LST) of 1400 (2 p.m.). The extended products have been validated with data collected during the Surface Heat

* *Corresponding author address*: Xuanji Wang, CIMSS/Univ. of Wisconsin-Madison, Madison, WI 53706; e-mail: xuanjiw@ssec.wisc.edu.

Budget of the Arctic Ocean (SHEBA) field experiment in the western Arctic, and with data from two Antarctic meteorological stations (Key, 2001; Maslanik, 2001; Stroeve, 2001; Pavolonis, 2002). A significant turning point occurred in the late 1980s and early 1990s corresponding to the changes in the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) indices (Thompson, 1998), making the time period of the APP-x data set ideal for the analysis of recent trends.

3. Recent Arctic Climate Trends

Trend analyses of cloud properties, surface properties and radiation components were performed using linear least squares regression with the 18 years of retrieved products. The standard F test was performed to determine statistical significance. In the results presented herein, confidence levels are noted in parentheses (%) after their corresponding decadal trend values. Trends were calculated for the area north of 60°N latitude as shown in Figure 2. Results are described for the Arctic overall, for the ocean area only, and for various regions within the Arctic.

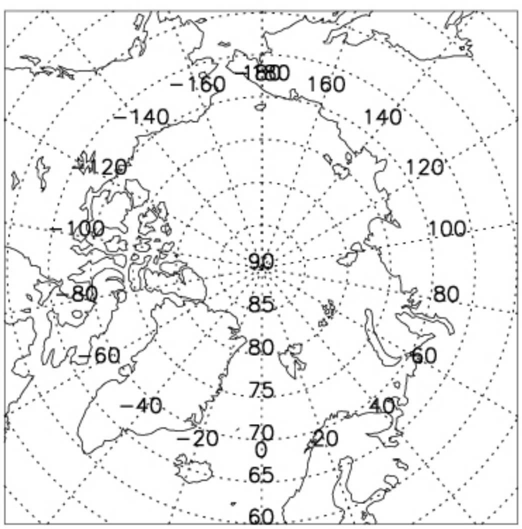

Figure 2. The study area of the Arctic region for APP data set.

3.1 Surface Temperature and Albedo

Figure 3 shows seasonal and annual trends of surface temperature and surface albedo in the APP-x data over the Arctic Ocean and surrounding land areas north of 60°N. The surface temperature has decreased at the decadal rate of -0.34°C in winter (December-February, where December data are from the previous year) but at a confidence level of only 69%. The broadband surface albedo has decreased -1.8% per decade (confidence level: 91%), but given that a large part of the Arctic region is dark throughout the winter, the albedo trend only represents areas between 60°N and approximately 76°N. Figure 4 shows a cooling trend in winter in the central and eastern Arctic. Our results are consistent with Serreze's (2000) finding of an increasing trend in Arctic winter sea ice extent, and with the satellite-derived surface temperature and precipitable water trends reported by Chen et al. (Wallace,) and Groves and Francis (2002). For the area north of 80°N, the APP-x surface temperature has decreased at -0.22°C per year (99%).

During spring, summer and autumn the surface temperature has increased over the Arctic at the decadal rates of 1.1°C, 0.68°C and 0.7°C, respectively (95%). The surface albedo has decreased at the decadal rate of -3.0% (99%) only in autumn, indicating a longer melt season and a later onset of freeze-up and snowfall. Excluding land, the ocean shows a strong warming trend, and the surface albedo has decreased both in summer and autumn at a confidence level higher than 95%. On an annual time scale the trend in surface temperature is dominated by spring and summer trends, with an overall increase of 0.54°C per decade (97%). The surface albedo has decreased at the decadal rate of -1.4% (92%). The annual warming is most obvious in northern Canada with a trend of 1.88°C degree per decade, followed by the Beaufort Sea and Greenland at the decadal rate of 1.04°C.

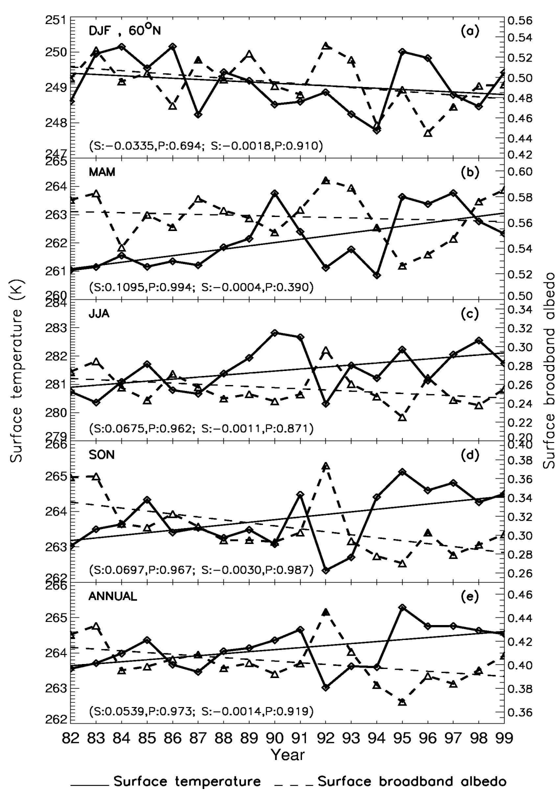

Figure 3. Time series and trends of surface skin temperature and broadband albedo in winter (December, January, February; DJF), spring (March, April, May; MAM), summer (June, July, August; JJA), autumn (September, October, November; SON) and the annual mean during the period of 1982–1999 for the Arctic north of 60°N. The numbers in parentheses are the trend slope per year ("S") and the F test confidence level ("P"). The first pair of S and P denotes the surface temperature trend (solid line) and the second pair is for the surface albedo (dashed line).

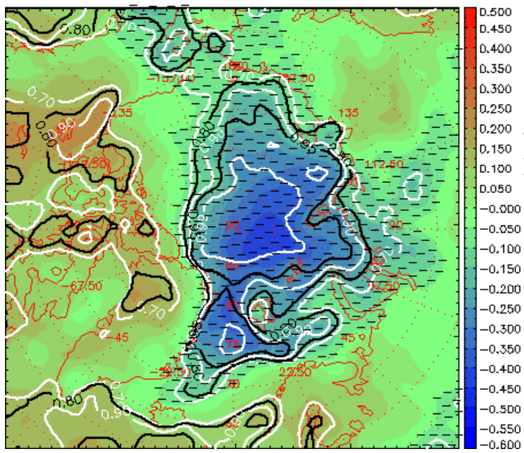

Figure 4. Surface skin temperature trends over the Arctic in winter, 1982-1999. Greenland is in the lower left portion of the image; Alaska is at the upper left; the North Pole is at the center. The colors represent the trend in degrees per year. Contours give the statistical level of confidence of the trend. Areas with cooling trends are marked with dashes.

3.2 CLOUD AND PRECIPITABLE WATER

Some cloud characteristics have also changed during the last two decades. In the Arctic winter cloud amount has decreased at the decadal rate of -4.9% (95%). The decrease is largest in the central Arctic Ocean as shown in Figure 5. Spring and summer cloud amount has been increasing at the decadal rates of 4.4% and 1.9%, respectively (100%). The increase in cloud amount is generally consistent with an increasing trend in cyclonic activity (Serreze, 2000) and an increasing trend in total precipitable water. On an annual time scale the seasonal trends cancel. Figure 6 gives the seasonal and annual trends of cloud amount and precipitable water (PW is from the NCEP Reanalysis). Over the entire Arctic, precipitable water shows a decreasing trend in winter at the decadal rate of –0.009 cm (91%). Over the ocean only there is a strong decreasing trend in PW during winter at the decadal rate of -0.01 cm (95%), while during spring and summer PW has been increasing at the decadal rates of 0.013 cm and 0.020 cm, respectively (95%). The decrease in PW during winter is consistent with the decreasing surface temperature and cloud amount trends in the APP-x data.

Cloud particle effective radius, defined as the ratio of the third to second moments of the particle size distribution, has been decreasing at the decadal rates of -2.3, -0.7, and -1.5 micrometers (99%) for spring, summer and autumn, respectively (not shown). This indicates a greater frequency of liquid phase cloud in the warmer troposphere, which agrees with tropospheric warming trends reported elsewhere (Overland, 2002). Cloud effective optical depth, defined as the product of the visible cloud optical depth and the cloud amount, has only changed significantly during the winter, at the decadal rate of -0.19 (91%). There are significant trends in cloud height only for the autumn and winter over the western Arctic Ocean, where cloud pressure has decreased at the rate of 60 hPa per decade (90%). If increasing cloud amount were due to increasing surface evaporation as might be expected with a warming trend, low cloud amount would probably increase as well. This does not appear to be the case.

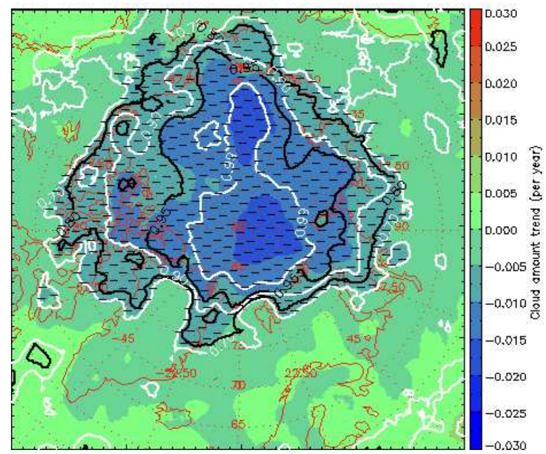

Figure 5. As in Figure 4, but for the cloud amount trend. Areas with decreasing cloud amount are marked with dashes.

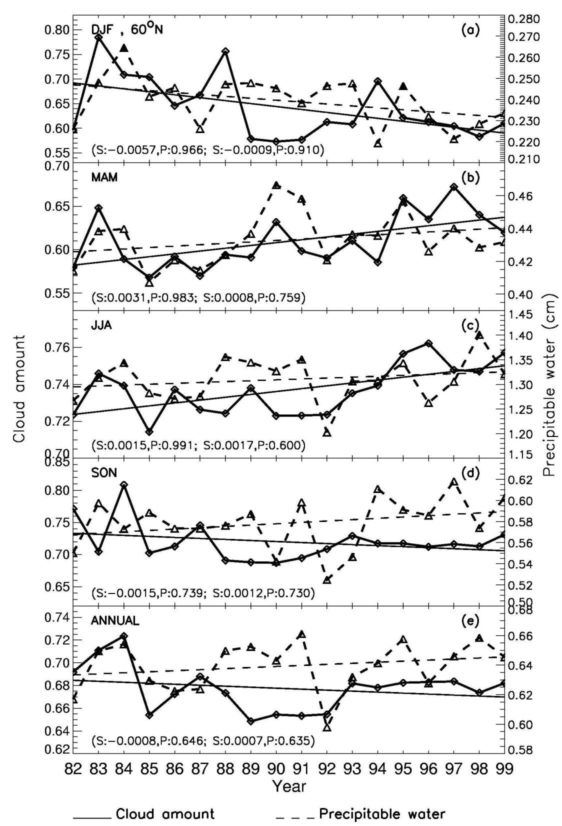

Figure 6. As in Figure 3, but for the cloud amount (solid) and precipitable water (dashed) trends.

3.3 Radiation Fluxes

Figure 7 shows the time series and trends of net shortwave, longwave and all-wave radiation fluxes at the surface in four seasons and annual mean in the Arctic over 1982 – 1999. There are no trends with confidence levels higher than 90%, except for a decreasing trend of net longwave radiation flux at the surface in winter at the decadal rate of $-3.4 W/m^2$. This is due to decreasing cloud cover.

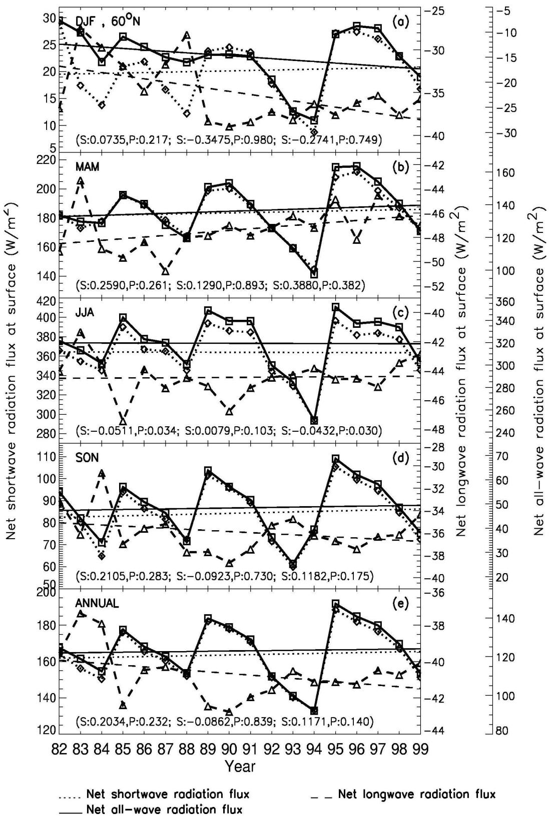

Figure 7. As in Figure 3, but for the net surface shortwave radiation flux (dotted), net longwave radiation flux (dashed), and net all-wave radiation flux (solid) trends.

4. CLOUD-RADIATION FEEDBACK

The cloud radiative effect, or "cloud forcing", is defined as the difference between the net all-sky flux and the net clear sky flux, so that a positive cloud forcing indicates a warming effect and a negative value indicates a cooling effect. Changes in cloud forcing will therefore reflect changes in surface temperature, surface albedo, and cloud properties, particularly cloud amount. The wintertime net cloud forcing, which is dominated by the longwave forcing, has decreased at a decadal rate of $-5.04 W/m^2$ (97%) (decreasing warming effect) in response to a decrease in cloud amount (Figure 8). In spring, increasing cloud amount results in a strong increase in the longwave cloud forcing (greater warming) but a decrease in the shortwave cloud forcing (greater cooling), so that the net effect is nearly zero. In summer the shortwave cloud forcing is much larger than in winter, and it dominates the net all-wave cloud forcing. The decreasing trend of the net cloud forcing in summer is $-5.03 W/m^2$ per decade (99%). The annual trend in net cloud forcing is $-3.56 W/m^2$ (98%), indicating an increased cooling effect.

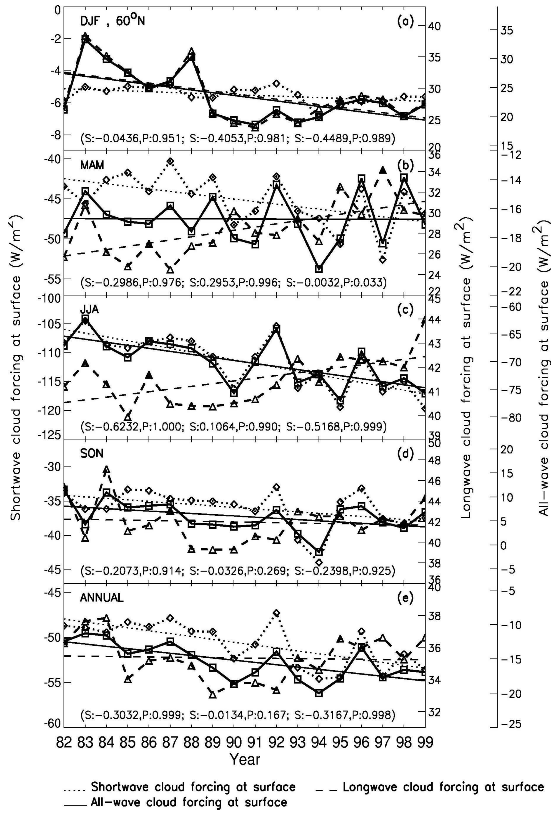

Figure 8. As in Figure 3, but for the surface shortwave cloud forcing (dotted), longwave cloud forcing (dashed), and net (all-wave) cloud forcing (solid) trends.

The cooling effect of clouds may be damping the increase in surface temperature to some degree; i.e., if cloud amount were not increasing then the surface temperature might be increasing at an even greater rate than what was found here and in other studies. The radiative interaction between clouds, surface temperature, and surface albedo, the cloud-radiation feedback, is such that there is no significant trend in net radiation during winter, spring, summer, or fall, even though there are trends in cloud and surface properties. It appears that during the sunlit part of the year the decreases in sea ice extent and albedo that result from surface warming modulate the increasing cloud cooling effect, resulting in little or no change in the surface radiation budget.

5. SUMMARY AND CONCLUSIONS

Satellite retrievals of surface, cloud, and radiation parameters over the Arctic region were used to investigate Arctic climate characteristics and its recent trends. Because of the Arctic unique underlying surface conditions, Arctic climate has its own characteristics as discussed in this paper. The present study indicates that the Arctic has been warming in spring, summer and autumn, with decadal rates of 1.1°C, 0.68°C, and 0.70°C, respectively. In winter the Arctic has been cooling at the decadal rate of -0.34°C, which is mainly due to cooling in the central Arctic ocean (north of 80°N), where the surface temperature has decreased at –0.22°C degree per year at the confidence level of as high as 99.7%. The Arctic surface broadband albedo also signals the warming trend of the Arctic at the decadal rate of -3.0% in autumn.

Results show that the Arctic has warmed and become cloudier in spring and summer, but has cooled and become less cloudy in winter. The surface albedo has decreased in autumn as a result of a longer melt period and later freeze-up. The radiative interaction between clouds, surface temperature, and surface albedo, the cloud-radiation feedback, is such that there is no significant trend in net radiation during winter, spring, summer, or fall, even though there are trends in cloud and surface properties. It appears that during the sunlit part of the year the decreases in sea ice extent and albedo that result from surface warming modulate the increasing cloud cooling effect, resulting in little or no change in the surface radiation budget. Additionally, the cooling effect of clouds may be damping the increase in surface temperature to some degree; i.e., if cloud amount were not increasing then the surface temperature might be increasing at an even greater rate than what was found here and in other studies.

6. REFERENCES

Curry, J.A., W. B. Rossow, D. Randall, J. L. Schramm, Overview of Arctic cloud and radiation characteristics. *J. Climate*, **9**(8), 1731-1764, (1996).

Fowler, C.W., personal communication. (2001).

Groves, D.G., J. A. Francis, Variability of the Arctic atmospheric moisture budget from TOVS satellite data. *J. Geophys. Res*., in press, (2002).

Key, J.R., "*The cloud and surface parameter retrieval (CASPR) system for polar AVHRR*". (Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, 59 pp, 2000).

Key, J.R., X. Wang, J. Stroeve, C. Fowler, Estimating the cloudy-sky albedo of sea ice and snow from space. *J. Geophys. Res*., **106**(D12), 12,489-12497, (2001).

Kistler, R., *et al*., The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and Documentation. *Bull. Amer. Meteorol. Soc*., **82**(2), 247-267, (2001).

Manabe, S., R.J. Stouffer, Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *Journal of Climate*, **7**(1), 5-23, (1994).

Manabe, S., M. J. Spelman, R.J. Stouffer, Transient response of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2 . Part II: Seasonal response. *Journal of Climate*, **5**(2), 105-126, (1992).

Maslanik, J.A., J. R. Key, C. W. Fowler, T. Nguyen, X. Wang, Spatial and Temporal Variability of Satellite-derived Cloud and Surface Characteristics During FIRE-ACE. *J. Geophys. Res*., **106**(D14), 15,233-15,249, (2001).

Meehl, G.A., W. M. Washington, CO_2 climate sensitivity and snow-sea-ice parameterization in an atmospheric GCM coupled to a mixed-layer ocean model. *Clim. Change*, **16**, 283-306, (1990).

Meier, W., J. A. Maslanik, J. R. Key, C. W. Fowler, Multiparameter AVHRR derived products for Arctic climate studies" *Earth Interactions*, **1**, paper no. 5 (electronic journal only), (1997).

Miller, J.R., G. L. Russell, Projected impact of climatic change on the freshwater and salt budgets of the Arctic Ocean by a GCM. *Geophys. Res. Lett*., **27**, 1183-1186, (2000).

Overland, J.E., W. Muyin, N. A. Bond, On the recent temperature changes in the western Arctic during Spring. *J. Climate*, **15**(13), 1702-1716, (2002).

Parkinson, C.L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, J. C. Comiso. Arctic sea ice extents, areas, and trends, 1978-1996. *J. Geophys. Res*., **104**(C9), 20,837-20,856, (1999).

Pavolonis, M.J., J. R. Key, X. Wang, Antarctic cloud radiative forcing at the surface estimated from the ISCCP D2 and AVHRR polar pathfinder data sets, 1985-*1993. presented at IEEE International Geoscience and Remote Sensing Symposium*, Toronto, Canada, June 23-28, 2002.

Rigor, I., R. L. Colony, S. Martin, Variations in surface air temperature observations in the Arctic, 1979-97. J. Climate, 13, 896-914, (2000).

Rossow, W.B., A.Walker, D. Beuschel, M. Roiter, "*International Satellite Cloud Climatology Project (ISCCP) Documentation of Cloud Data*" (World Climate Research Programme, NASA, Goddard Institute of Space Studies, 115 pp, 1996).

Serreze, M.C., et al., Observational evidence of recent change in the northern high-latitude environment. *Climate Change*, **46**, 159-207, (2000).

Stroeve, J., J. Box, C. Fowler, T. Haran, J. Key, Intercomparison Between in situ and AVHRR Polar Pathfinder-derived Surface Albedo over Greenland, *Remote Sensing of the Environment*, **75**/3,360-374, (2001).

Thompson, D.W.J., J. M. Wallace, The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett*., **25**(9), 1297-1300, (1998).

Vinnikov, K.Y., *et al*., Global warming and northern hemisphere sea ice extent. *Science*, **286**, 1934-1937, (1999).

Wallace, J.M., Y. Zhang, L. Bajuk, Interpretation of interdecadal trends in Northern Hemisphere surface air temperature. *J. Climate*, **9**, 249-259, (1996).