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A 21 year record of Arctic sea-ice extents and their regional, seasonal and monthly variability and trends

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ABSTRACT. Satellite passive-microwave data have been used to calculate sea-ice extents over the period 1979–99 for the north polar sea-ice cover as a whole and for each of nine regions. Over this 21 year time period, the trend in yearly-average ice extents for the ice cover as a whole is $-32\,900 \pm 6100$ km^2 a^{-1} (-2.7 ± 0.5% per decade), indicating a statistically significant reduction in sea-ice coverage. Regionally, the reductions are greatest in the Arctic Ocean, the Kara and Barents Seas and the Seas of Okhotsk and Japan; and seasonally, the reductions are greatest in summer, for which season the 1979–99 trend in ice extents is $-41\,600 \pm 12\,900$ km^2 a^{-1} (-4.9 ± 1.5% per decade). On a monthly basis, the reductions are greatest in July and September for the north polar ice cover as a whole, in September for the Arctic Ocean, in June and July for the Kara and Barents Seas, and in April for the Seas of Okhotsk and Japan. Of the nine regions, only the Bering Sea and the Gulf of St Lawrence show positive ice-extent trends on a yearly-average basis. However, the increases in these two regions are not statistically significant. For the north polar region as a whole, and for the Arctic Ocean, the Seas of Okhotsk and Japan, and Hudson Bay, the negative trends in the yearly averages are statistically significant at a 99% confidence level.

INTRODUCTION

Sea ice is an integral component of the Arctic climate system, restricting exchanges of heat, mass and momentum between the ocean and the atmosphere, reflecting most of the solar radiation incident upon it, releasing salt to the underlying ocean during freezing and transporting fresh water Equatorward through sea-ice advection. It is also of vital importance to the ecology of the Arctic, serving as a habitat for organisms living within it, a platform for animals wandering over it and either a help or a hindrance to numerous marine plant and animal species. Hence, changes in the sea-ice cover can have many outreaching effects on other elements of the polar climate and ecological systems. Furthermore, through the interconnectedness of the climate system, major changes in the sea-ice cover could have more far-reaching effects, extending well beyond the polar regions. For instance, changes in the ice transport of cold fresh water southward in the Greenland Sea could impact the deep-water formation in the northern North Atlantic and thereby affect the "conveyor-belt" circulation that cycles through much of the global ocean.

Considerable attention has been given recently to decreases in Arctic sea-ice extents detected through analysis of satellite passive-microwave data since late 1978 (e.g. Johannessen and others, 1995; Maslanik and others, 1996; Bjørgo and others, 1997; Parkinson and others, 1999). These studies have emphasized decreases examined for the record length as a whole or for annual or seasonal averages. Here we update the annual and seasonal decreases to a 21 year record through the end of 1999, and additionally present time series and trends for each month. Results are given for the Northern Hemisphere as a whole and for each of nine regions, identified in Figure 1. Although a much longer record would be desired (if available), this 21 year period does include El Niño and La Niña episodes, positive and negative phases of the North Atlantic Oscillation and the Arctic Oscillation, and major volcanic eruptions of El Chichón, Mexico (28 March–4 April 1982), and Mount Pinatubo, Philippines (15 June 1991). Hence it provides researchers studying those phenomena with a chance to examine effects they may have had on the Arctic sea-ice cover, thereby helping to quantify the respective climate interconnections.

DATA AND METHODOLOGY

The data used in this study are satellite passive-microwave data from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) and three U.S. Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imagers (SSM/Is). Microwave data are particularly applicable for sea-ice research because the microwave emissions of sea ice and liquid water differ significantly, thereby allowing a ready distinction between ice and water from the satellite microwave data. Complications arise from the diversity of ice surfaces and from melt ponding and snow cover on the ice, but the satellite passive-microwave data still allow a clear depiction of the overall distribution of the ice and thereby allow a calculation of ice extents (areas covered by ice of concentration at least 15%).

The SMMR was operational on an every-other-day basis for most of the period 26 October 1978 to 20 August 1987, and the sequence of SSM/Is has been operational on a daily basis for most of the period since 9 July 1987. The SMMR and SSM/I data have been used to create a consistent dataset of sea-ice concentrations (per cent areal coverages of ice) and extents through procedures described in Cavalieri and others (1999). Briefly, the method used for obtaining consistency was one of matching sea-ice extents and areas during periods of overlap

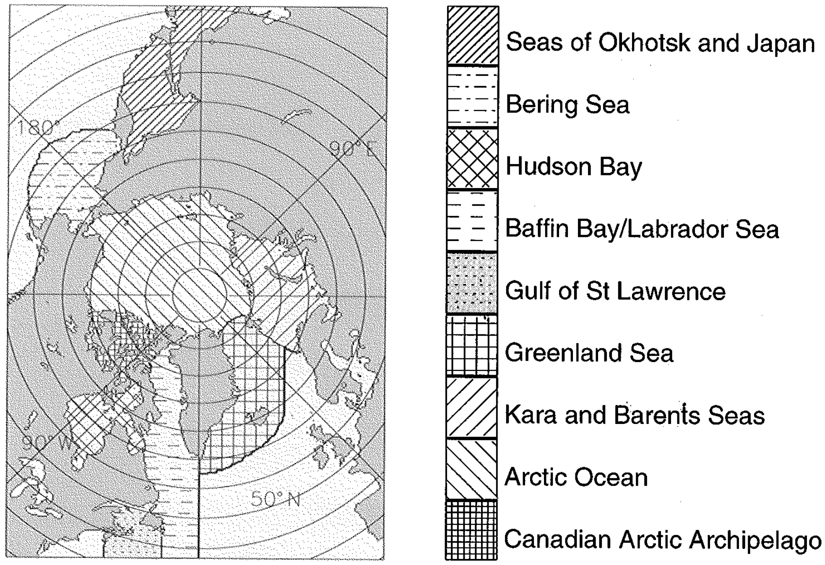

Fig. 1. Identification of the nine regions used in the analysis.

between consecutive sensors. This procedure reduced errors resulting from different sensor frequencies, footprint sizes, observation times and calibrations. While the periods of overlap were shorter than desirable, the average ice-extent differences between sensors were reduced to $<0.05\%$, and the average ice-area differences were reduced to 0.6% or less.

The ice concentrations are gridded to a resolution of approximately $25\,\text{km} \times 25\,\text{km}$ (NSIDC, 1992) and are available at the U.S. National Snow and Ice Data Center (NSIDC) in Boulder, CO. The ice extents are calculated by adding the areas of all gridcells containing ice with a calculated concentration of at least 15%. This is done for each of the nine regions identified in Figure 1 and for the total.

Trends in the ice extents are determined through linear least-squares fits separately on the monthly-averaged, seasonally averaged and yearly-averaged data. The trends are calculated for each of the nine regions and the total, and in each case an estimated standard deviation of the trend (σ) is calculated following Taylor (1997). Trends are considered statistically significant in those cases where the trend magnitude exceeds 1.96σ, signifying a 95% confidence level that the slope is non-zero. Trends with magnitudes exceeding 2.58σ are considered significant at a 99% confidence level (Taylor, 1997).

DISCUSSION

Satellite technology provides a powerful resource for monitoring the Arctic sea-ice cover's distribution and extent, and we have taken advantage of this by using this technology to quantify changes in the Arctic ice cover since the late 1970s, with results presented in Table 1 and Figures 2–4 for the 21 year period 1979–99. Most notably, the ice cover as a whole has negative trends for every month, with a trend in the annual averages of $-32\,900 \pm 6100\,\text{km}^2\,\text{a}^{-1}$.

Because of the sharp contrast between the microwave emissivities of liquid water and ice, the satellite passive-microwave data are particularly good at revealing the distribution of the sea-ice cover, which in turn allows calculation of the ice extent and determination of changes in ice extent. These satellite data are not as appropriate for determining changes in ice thickness, but analyses of submarine data have revealed a thinning of the ice cover (e.g. Rothrock and others, 1999) that is even more dramatic, percentage-wise, than the ice-extent reductions reported here. (However, Winsor (2001) reports that the thinning did not continue in the 1990s, at least over a limited region from north of Alaska to the North Pole.)

Of course neither the satellite data nor the submarine data can explain the causes of the sea-ice changes or predict future changes. If the decreasing ice coverage is tied most closely to an ongoing Arctic warming (Martin and others, 1997; Serreze and others, 2000) that continues, then the ice cover is likely to continue to decrease as well; but if the sea-ice changes are tied more closely to oscillatory behaviors in the climate system, such as the North Atlantic Oscillation and the Arctic Oscillation (as suggested by, e.g., Deser and others, 2000; Morison and others, 2000; Parkinson, 2000), then it is likely that there will also be fluctuations between periods of sea-ice decrease and periods of sea-ice increase.