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Analysis of merged SMMR-SSMI time series of Arctic and Antarctic sea ice parameters 1978–1995

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Abstract. The most consistent means of investigating the global sea ice cover is by satellite passive microwave sensors, as these are independent of illumination and cloud cover. The Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) provide information on the global sea ice cover from 1978 to present. The two instruments flew simultaneously during a 6-week overlap period in July and August 1987, thus enabling intercomparison of the two sensors. Brightness temperatures are corrected for instrument drift and calibration differences in order to produce continuous time series of monthly averaged Arctic and Antarctic sea ice extent and sea ice area through the use of the NOrwegian Remote Sensing EXperiment (NORSEX) algorithm, which relates brightness temperatures to ice concentration. Statistical analysis on the time series estimates the decreases in Arctic ice extent and ice area to be 4.5% and 5.7%, respectively, during the 16.8-year observation period. The overall trends established here serve to better define and strengthen earlier assertions of a reduced ice cover, based on analysis of SMMR and SSMI data taken separately. These results are consistent with GCM simulations that suggest retreat of the sea ice cover under global warming scenarios.

Introduction

Changes in global mean temperature are predicted to exceed their natural variability between the decades 1980 and 2010, there is also a 95% probability that the observed temperature increase of 0.4°–0.6° C over the last century is due to man's activities [*Hasselmann et al.*, 1995]. The predicted warming is strongest in the Arctic, roughly 3-4 °C during the next 50 years, but also considerable in the Antarctic, roughly 1-2 °C for the same period [*Mitchell et al.*, 1995]. The enhanced warming in the polar regions suggests that sea ice, an important component of the climate system, could be one of the early integrated indicators of global warming.

Previous studies of the ice cover from the 1978-87 Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) record showed significant decreases of the Arctic ice extent with a trend of 2.4% per decade [*Gloersen and Campbell*, 1991], the sum of larger positive and negative regional trends [*Gloersen et al.*, 1996], but no significant trend in the Antarctic. *Johannessen et al.* [1995] analyzed data from the subsequent Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) and found a greater trend of -4.3 % per decade in ice extent from 1987–1994, but no significant trend in the Antarctic. However, the trends from these short time series can be substantially influenced by even a single unusual year, perhaps associated with quasi-periodic variability [*Gloersen*, 1995].

The objective for our study is therefore to intercompare and match SMMR and SSMI data, based on a 6-week overlap period, to produce continuous 1978–95 sea ice time series and perform a trend analysis on Arctic and Antarctic ice parameters. The primary parameters or variables are: *ice extent*, the area within the ice-ocean margin limited by the 15% ice concentration contour, and *ice area*, the area of ice-covered ocean.

Achievement of the above objective requires us to: 1) Investigate the instrument stability of SMMR and SSMI, 2) intercompare and match SMMR and SSMI ice concentrations by adjusting the brightness temperature (T_B) and ice concentration algorithm parameters, 3) produce merged SMMR-SSMI time series of monthly averaged Arctic and Antarctic sea ice parameters and, 4) analyze them for trends. These are discussed in the following sections.

Instrument drift analysis

A detected trend in T_Bs over open ocean can be attributed either to instrument drift or to trends in geophysical conditions [*Gloersen et al.*, 1992]. The SMMR T_Bs distributed on CD-ROM by the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, are corrected for instrument drift based on fluctuations found from averaging T_Bs from 50° latitude poleward to the sea ice edge, as described by *Gloersen et al.* [1992]. However, no "controlled" in-situ meteorological or oceanographic data were investigated to explain the observed fluctuations in the T_Bs. We therefore chose to reanalyze the SMMR T_Bs on CD-ROM for any remaining drift. Regarding the two separate SSMI sensors, F-8 and F-11, the T_B record for each sensor is too short to permit a reliable sensor drift analysis.

To detect possible drifts in the SMMR T_Bs and at the same time have control over meteorological and oceanographic parameters, we selected a high-latitude

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open ocean area (200,000 km^2, centered at 66° N, 2° W) where meteorological and oceanographic time series were available from weather ship "Mike" (66° N, 2° E, in the eastern part of the test area). In order to investigate other representative areas, another high-latitude open ocean area (600,000 km^2, centered at 52° N, 40° W) in the Northern Hemisphere, as well as two high-latitude open ocean areas (800,000 km^2 each, centered at 53° S, 40°E and 53° S, 135° W) in the Southern Hemisphere were selected. However, from these three areas there were no high-quality time series of meteorological or oceanographic data that covered the study period.

Spatially averaged T_Bs were calculated for each of the four areas. A linear least squares fit (LSF) was performed on anomalies computed from differences between monthly values and corresponding normal-year monthly values. Linear trends for the four areas were found for SMMR's 37 GHz horizontally polarized (H) and vertically polarized (V) channels, +0.19 K/yr and -0.21 K/yr, respectively.

Analyses of meteorological and oceanographic data (wind speed, pressure, precipitation, near surface temperature and sea surface temperature) from station "Mike" do not explain the observed T_B trends for this area. First, a T_B trend induced by one or more of the analyzed meteorological or oceanographic parameters should be in the same direction for both polarizations [*Wilheit*, 1978], which was not the case for the above listed trends. Second, it is not likely that the meteorological or oceanographic parameters should be the cause of the above listed trends, as the individual trends for each channel in the different areas generally have the same sign, and are of the same order, for all areas on both hemispheres. For this to be due to other than instrument drift, there would have to be a similar systematic change in meteorological and oceanographic parameters in both areas in both hemispheres simultaneously.

Our instrument trends for SMMR's 37 GHz H and V are of the same sign and magnitude as linear representations of the fluctuations described in *Gloersen et al.* [1992], implying that corrected T_Bs based on their fluctuations, as distributed on the NSIDC CD-ROMs, would not completely account for instrument drift. We concluded there to be a remaining instrument drift in the SMMR T_Bs distributed on CD-ROM, which we have corrected.

Sea ice concentration intercomparison and match-up

In addition to drift correction, one must intercompare and match the sensor data. It is recommended [*Zabel and Jezek*, 1994] that this procedure be performed at the geophysical product level, e.g. sea ice concentrations. Here, the sea ice intercomparison and match-up process involves first adjusting the SMMR and SSMI T_Bs, then adjusting the ice concentration algorithm that is applied to the adjusted T_Bs.

In a previous study [*Jezek et al.*, 1993], Antarctic ice sheet T_Bs from SMMR and SSMI were matched. However, applying the coefficients estimated by *Jezek et al.* [1993] to sea ice T_Bs is successful only for sea ice concentrations above 70% [*Zabel and Jezek*, 1994]. In our study, sea ice concentrations down to 15% need to be included, so therefore we performed our own T_B intercomparison and adjustment over compact sea ice.

We chose to perform this procedure in the Antarctic, where winter conditions prevailed during the overlap period. The summer conditions in the Arctic, with a highly emissive wet snow cover and low emissivity meltponds, make match-up difficult as the relatively unstable diurnal summer emissivity properties of the surface [*Parkinson et al.*, 1987] may have changed between the SMMR and SSMI overpasses. Because independent buoy observations, primarily wind, compare better with wind estimates from SSMI radiances than from SMMR radiances, SMMR T_Bs are corrected to match the "true" SSMI T_Bs [*Zabel and Jezek*, 1994]. Following the approach *Jezek et al.* [1993] used for calibrating T_Bs over ice sheets, a strong linear relationship was established between SMMR and SSMI T_Bs over sea ice. The LSF estimated coefficients were used on all SMMR T_Bs to match them to the SSMI T_Bs.

The NORSEX algorithm [*Svendsen et al.*, 1983] was used here to calculate individual pixel sea ice concentrations. This algorithm calculates ice concentration using channels 18 GHz V and 37 GHz V for SMMR and 19 GHz V and 37 GHz V for SSMI, together with monthly average atmospheric surface temperature. Emissivities and atmospheric opacities taken from measurements in the Arctic [*NORSEX Group*, 1983] and Antarctic [*Grenfell et al.*, 1994] are also used in the algorithm. The NORSEX algorithm is used in combination with filters constructed to reduce false sea ice signatures from weather effects [*Gloersen and Cavalieri*, 1986; *Cavalieri et al.*, 1991]. A sea-mask file is used to limit land effects on T_Bs. For consistency, the SSMI land-mask was used for both SMMR and SSMI data. Due to differences in latitudinal coverage between SMMR and SSMI, ice concentrations poleward of 84 degrees were not included in the match-up.

Individual pixel ice concentrations were matched by slightly tuning the values for optical depth and emissivities originally based on *NORSEX Group* [1983] and *Grenfell et al.* [1994] to better match the new adjusted T_Bs and adjusting the SMMR weather filter. The tuned values for optical depth and emissivities were within the errors reported by *NORSEX Group* [1983] and *Grenfell et al.* [1994].

Ice extent and ice area were calculated from individual pixel ice concentrations. The overlap period agreement, based on SSMI/SMMR ratios of ice parameters in the Arctic, was found to be within 0.31% for ice extent and 0.02% for ice area. For the Antarctic the same relations are: 0.04% for ice extent and 0.07% for ice area. The difference between the agreement in the Arctic and the Antarctic is due to meltponds and wet snow cover during Arctic summer, which highly influence the T_Bs.

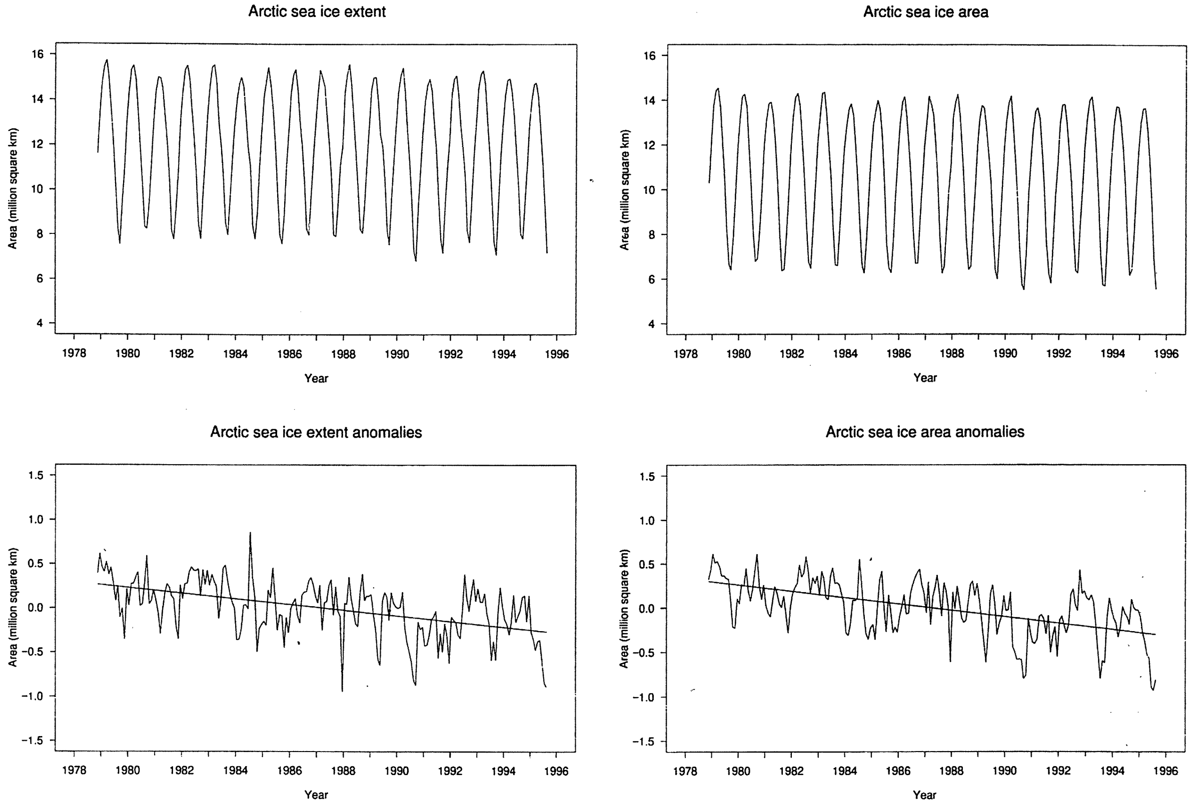

Figure 1. Monthly averages (top) and anomalies (bottom) of Arctic ice extent and ice area, November 1978 – August 1995. The linear curve represents the slope from the LSF analysis.

Sea ice time series and trend analysis

From the above procedures, we obtained a 16.8 year record of Arctic and Antarctic ice extent and ice area. The area north of 84° is added to the computed monthly values for the Arctic, consistent with other studies [*Gloersen and Campbell*, 1991; *Johannessen et al.*, 1995]. Fig. 1 shows time series and corresponding anomalies with trends from the LSF analysis for the Arctic.

The greatest trends were found in Arctic ice extent (-4.5%) and ice area (-5.7%), significant at the 99% confidence level, see Table 1. The presence of autocorrelation in the error terms influences the confidence in the regression. To address the problem, we effectively eliminated the autocorrelation by randomly removing 4- and 5-month blocks of data, and then re-ran the regressions on the altered time series. The re-estimated probability values of the trends in Arctic ice extent and ice area were consistently less than 0.01, giving us confidence in the regression results using the entire data set.

The observed trends in ice extent and ice area are at least one order of magnitude higher than the overlap period differences between the two sensors. The ice extent and ice area trends found here are between the trends found previously [*Johannessen et al.*, 1995] using separately treated SMMR and SSMI T_B data. This conformance supports our contention that the SMMR-SSMI merging was successful.

The importance of correcting for instrument drift is evident, as the trends are smaller and less statistically significant when T_Bs are used as is from the CD-ROMs: -2.8% at the 93% confidence level for ice extent and -3.8% at the 96% confidence level for ice area.

Table 1. Summary of trend analysis on Arctic and Antarctic sea ice extent and sea ice area. Percent change, $\Delta_{\%}$, and areal change, Δ_A, are based on average parameter values. The observation period, T_{obs}, is the length of the combined time series, i.e. 16.8 years.

Parameter	Slope ($\times 10^6$km^2/yr)	Estimated std. dev. of the slope ($\times 10^6$km^2/yr)	$\Delta_{\%}$ during T_{obs}	Δ_A during T_{obs} ($\times 10^6$km^2)	Conf. level (%)
		Arctic			
Ice extent	-0.032	0.004	-4.5	-0.54	99
Ice area	-0.036	0.004	-5.7	-0.61	99
		Antarctic			
Ice extent	-0.008	0.007	-1.1	-0.13	75
Ice area	-0.003	0.006	-0.5	-0.05	35

Conclusion

The most important technical achievement in this study is the merging of SMMR and SSMI data at the geophysical parameter level, to produce a 16.8-year continuous sea ice time series. An advantage of the merged time series is its increased statistically reliability (more degrees of freedom) compared to analyses of separate SMMR and SSMI records. Another advantage is the reduced influence of quasi-cyclic sea ice variability on linear trend estimates [*Gloersen*, 1995].

Our study more firmly establishes a reduction of the Arctic ice cover from 1978–1995, which may well be an early signal of global greenhouse gas warming. In particular, we found decreases of -4.5% in ice extent and -5.7% in ice area in the Arctic, both at the 99% confidence level. The findings of *Maslanik et al.* [1996] suggest that these overall trends are due largely to reduced ice in the Siberian sector of the Arctic Ocean in summer in recent years, though we perform no regional or temporal breakdown here.

Our merged SMMR-SSMI sea ice time series can serve as a baseline data set against which related climatic observations and model simulations of temperature and ice extent can be compared. Our analysis scheme can also incorporate new SSMI data as acquired, thus extending the microwave sea ice record for "operational monitoring" of the global ice cover.

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