

Variability of Antarctic sea ice 1979 – 1998

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Received 22 November 2000; revised 23 July 2001; accepted 13 September 2001; published 16 May 2002.

[1] The principal characteristics of the variability of Antarctic sea ice cover as previously described from satellite passive microwave observations are also evident in a systematically calibrated and analyzed data set for 20.2 years (1979 – 1998). The total Antarctic sea ice extent (concentration >15%) increased by $11,180 \pm 4190 \text{ km}^2 \text{ yr}^{-1}$ ($0.98 \pm 0.37\%$ (decade)⁻¹). The increase in the area of sea ice within the extent boundary is similar ($10,860 \pm 3720 \text{ km}^2 \text{ yr}^{-1}$ and $1.26 \pm 0.43\%$ (decade)⁻¹). Regionally, the trends in extent are positive in the Weddel Sea ($1.4 \pm 0.9\%$ (decade)⁻¹), Pacific Ocean ($2.0 \pm 1.4\%$ (decade)⁻¹), and Ross ($6.7 \pm 1.1\%$ (decade)⁻¹) sectors, slightly negative in the Indian Ocean ($1.0 \pm 1.0\%$ (decade)⁻¹), and strongly negative in the Bellingshausen-Amundsen Seas sector ($9.7 \pm 1.5\%$ (decade)⁻¹). For the entire ice pack, ice increases occur in all seasons, with the largest increase during fall. On a regional basis the trends differ season to season. During summer and fall the trends are positive or near zero in all sectors except the Bellingshausen-Amundsen Seas sector. During winter and spring the trends are negative or near zero in all sectors except the Ross Sea, which has positive trends in all seasons. Components of interannual variability with periods of about 3 – 5 years are regionally large but tend to counterbalance each other in the total ice pack. The interannual variability of the annual mean sea ice extent is only 1.6% overall, compared to 6 – 9% in each of five regional sectors. Analysis of the relation between regional sea ice extents and spatially averaged surface temperatures over the ice pack gives an overall sensitivity between winter ice cover and temperature of 0.7% change in sea ice extent per degree Kelvin. For summer some regional ice extents vary positively with temperature, and others vary negatively. The observed increase in Antarctic sea ice cover is counter to the observed decreases in the Arctic. It is also qualitatively consistent with the counterintuitive prediction of a global atmospheric-ocean model of increasing sea ice around Antarctica with climate warming due to the stabilizing effects of increased snowfall on the Southern Ocean.

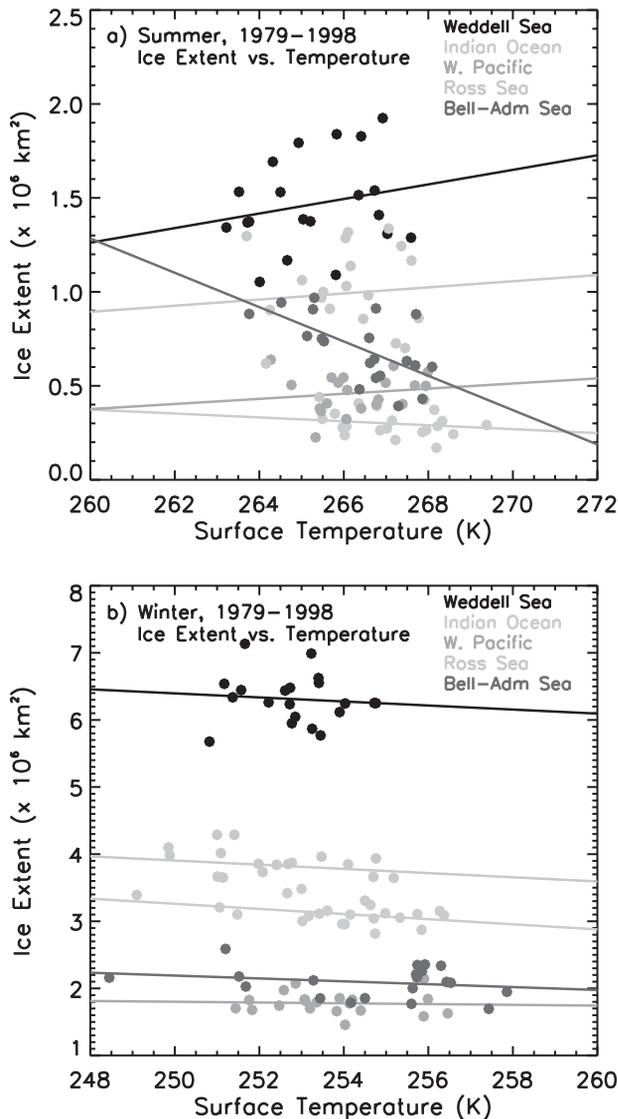


Figure 22. Relations between regionally averaged sea ice extents and regionally averaged surface temperatures over the ice pack as derived from satellite infrared for (a) summer month of January showing generally consistent relations from sector to sector and (b) winter month of July showing negative relations between sea ice extents and temperature. See color version of this figure at back of this issue.

for direct comparison with satellite data sets, the mean trend was found to be a slight cooling at -0.008 ± 0.016 , with 12 stations having negative trends and 9 stations having positive trends. Such general cooling during the last 20 years is also suggested by satellite infrared data [Comiso, 2000]. Qualitatively, these results are consistent with trend values shown in Tables 10 and 11.

8. Effects of the Antarctic Circumpolar Wave

[49] In the sea ice extent curves for the five Antarctic sectors (Figures 3–7) one can visualize the effects of a wave occasionally influencing a given region on the basis of a low-frequency wavelike envelope superimposed on the seasonal oscillations. One possibility for wavelike phenomena is the ACW, characterized by a pattern of wave number 2 and circumpolar migration time of 8 years [White and Peterson, 1996]. Their initial ACW observation has been confirmed more recently with differ-

ent techniques [Gloersen and Huang, 1999; Gloersen and White, 2001]. Gloersen and Huang [1999] utilized a combination of complex singular-value decomposition (CSVD) and empirical mode decomposition (EMD) [Huang et al., 1998] to isolate the ACW as residing principally in the quasiquadrennial (QQ) mode separated by the EMD. The Hoffmueller diagram [Huang et al., 1998, Figure 6a] clearly depicts several cycles of the ACW. Here we utilize the data array, which was the basis of Huang et al.'s [1998] Figure 6, with ice extents in 1° sectors around the South Pole to produce sums of the QQ oscillations in each of five sectors (Table 1) as well as the entire pack. These sums are shown in Figure 23 for comparisons with ice extent variations in Figures 2–7. Although five sectors is not optimum for displaying the characteristics of a wave number 2 pattern, the ACW can be discerned. For example, comparing the results in the Hoffmueller diagram [Gloersen and Huang, 1999] for a persistent ACW trough that begins at 0°E in 1986, in Figure 23 the averaged trough is shown in the Weddell sector also in 1986, in the Indian sector in 1987, in the western Pacific sector in mid-1988, in the Ross sector in mid-1991, and finally, in the B/A sector in 1993.

[50] Although the QQ oscillations associated with the ACW are prominent, the magnitude of their amplitudes ($\leq 0.08 \times 10^6 \text{ km}^2$ peak to peak) is only $\approx 1/25$ compared to the maximum interannual deviations in extent ($\leq 2 \times 10^6 \text{ km}^2$ in Figures 3b–7b). The amplitudes of the QQ oscillations are also only $\approx 1/3$ compared to the 3–5 cycles of interannual variability (amplitudes $\leq 0.26 \times 10^6 \text{ km}^2$), as deduced from the multivariate analysis and shown in Table 4 and the fitted cycles in Figures 3b–7b. Therefore the interannual variability associated with the ACW appears to be only part of the total quasi-periodic interannual variability and small compared to the total interannual variability.

9. Discussion and Conclusions

[51] A primary result of this analysis of the 20 years of measurements of sea ice concentration on the Southern Ocean is the $+11,181 \pm 4190 \text{ km}^2 \text{ yr}^{-1}$ ($+0.98 \pm 0.37\% \text{ (decade)}^{-1}$) increase in sea ice extent and a very similar $+10,860 \pm 3720 \text{ km}^2 \text{ yr}^{-1}$ ($+1.26 \pm 0.43\% \text{ (decade)}^{-1}$) increase in sea ice area. Regionally, the trends in extent are positive in the Weddell Sea ($1.4 \pm 0.9\% \text{ (decade)}^{-1}$), Pacific Ocean ($2.0 \pm 1.4\% \text{ (decade)}^{-1}$), and Ross Sea ($6.7 \pm 1.1\% \text{ (decade)}^{-1}$) sectors, slightly negative in the Indian Ocean ($-1.0 \pm 1.0\% \text{ (decade)}^{-1}$), and negative in the Bellinghshausen/Amundsen Seas sector ($-9.7 \pm 1.5\% \text{ (decade)}^{-1}$). An overall increase in Antarctic sea ice cover, during a period when global climate appears to have been warming by $0.2 \text{ K (decade)}^{-1}$ [Hansen et al., 1999], stands in marked contrast to the observed decrease in the Arctic sea ice extent of $-34,300 \pm 3700 \text{ km}^2 \text{ yr}^{-1}$ ($-2.8 \pm 0.3\% \text{ (decade)}^{-1}$) and sea ice area of $-29,500 \pm 3800 \text{ km}^2 \text{ yr}^{-1}$ ($-2.8 \pm 0.4\% \text{ (decade)}^{-1}$) in sea ice area [Parkinson et al., 1999]. The observed decrease in the Arctic has been partially attributed to greenhouse warming through climate model simulations with increased CO_2 and aerosols [Vinnikov et al., 1999]. As discussed in section 1, an increasing Antarctic sea ice cover is consistent with at least one climate model that includes coupled ice-ocean-atmosphere interactions and a doubling of CO_2 content over 80 years [Manabe et al., 1992].

[52] Another main aspect of the results is the seasonality of the changes, being largest in autumn in both magnitude ($+24,700 \pm 17,500 \text{ km}^2 \text{ yr}^{-1}$) and percentage ($+2.5 \pm 1.8\% \text{ (decade)}^{-1}$) and second largest in summer ($+6700 \pm 12,600 \text{ km}^2 \text{ yr}^{-1}$ and $+1.7 \pm 3.2\% \text{ (decade)}^{-1}$) in terms of percentage change. The changes for the winter season ($+7400 \pm 8500 \text{ km}^2 \text{ yr}^{-1}$ and $+0.4 \pm 0.5\% \text{ (decade)}^{-1}$) and for spring ($+10,100 \pm 14,000 \text{ km}^2 \text{ yr}^{-1}$ and $+0.7 \pm 1.0\% \text{ (decade)}^{-1}$) are small as a fractional change. On a regional basis the trends differ season to season. During summer and fall the trends are positive or near zero in all sectors except the Belling-

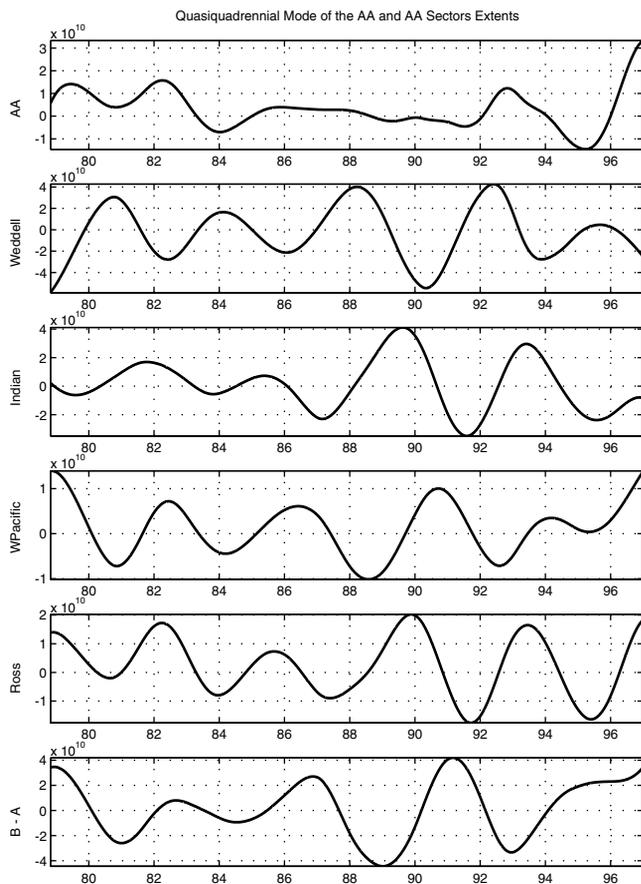


Figure 23. QQ modes of the sea ice concentration oscillations by regional sector. These QQ modes are obtained by summing over the regional sectors the results of the EMD of sea ice concentrations in 1° longitudinal sectors around the pole by *Gloersen and Huang [1999]*. See color version of this figure at back of this issue.

shausen/Amundsen Seas sector. During winter and spring the trends are negative or near zero in all sectors except the Ross Sea, which has positive trends in all seasons.

[53] In the context of climate change the sensitivity of the sea ice to changes in temperature is of particular interest. Analysis of the relation between regional sea ice extents and spatially averaged surface temperatures over the ice pack gives an overall sensitivity between winter ice cover and temperature of -0.70% change in sea ice extent per degree Kelvin ($-0.11 \pm 0.09 \times 10^6 \text{ km}^2 \text{ K}^{-1}$). A change in the winter ice extent of 0.70% corresponds to a latitudinal change in the average position of ice edge of $<10 \text{ km}$ or a meridional change of $<0.1^\circ$, which is small compared to some previous estimates [e.g., *Parkinson and Bindshadler, 1984*]. For summer some regional ice extents vary positively with temperature, and others vary negatively.

[54] The validity of the derived decadal-scale trends depends on two key aspects of this 20 year data set. One is the long-term relative accuracy of the data from multiple satellites with somewhat different sensors and the data processing methodology as described by *Cavalieri et al. [1999]*. The changes in sea ice cover as small as 1% (decade) $^{-1}$ may have climatic significance. This required relative accuracy and long-term data consistency could not have been achieved without the 4–6 week periods of overlap from successive satellites, which enabled the algorithm adjustments to make the derived sea ice extents and areas match. Even though the instrumental differences between satellites are small, it has not been possible to understand the differences well enough to provide a satisfactory intercalibration any other way.

[55] The second key aspect is the complete spatial coverage on daily timescales that allowed the spatial and temporal variability to be quantified adequately in relation to the trends. The characterization of the interannual variability in particular has allowed a calculation of trends that is largely independent of the effects of the periodic components of the variability. In addition, the analysis of data over 2 decades provides some indication of the interdecadal variability of the sea ice cover and provides a basis for future analysis of continuing observations for interdecadal changes. Determination of such interdecadal changes will be particularly important as sea ice changes might accelerate with an increase in climate warming.

[56] The interannual variability of the annual mean sea ice extent is only 1.6% overall, compared to $6\text{--}9\%$ in each of five regional sectors. The total variability in the monthly deviations in sea ice extent is 3.4% overall and from 8 to 15% in the individual sectors. From the first 10 years to the second 10 years there appears to be a decrease in the variability from 4.0 to 2.7% . Also, there appears to be a decline in the effectiveness in which the anomalies from sector to sector offset each other in the overall spatial average. Analysis of the relative trends in ice extent and ice area imply increases in ice concentration in the western Pacific and Ross Sea sectors, which could be associated with decreases in variability in those regions.

[57] Although there are significant components of interannual variability with periods of $3\text{--}5$ years, these represent only about $20\text{--}40\%$ of the total variability in the monthly deviations of the mean. Inclusion of a periodic component in the MOLS gives trends that are considered to be better values than the OLS trends. Nevertheless, the inclusion of about five cycles in the 20 year data set and the smallness of the periodic amplitudes minimize the effect on the calculated linear trends by the OLS method. Therefore the MOLS and the OLS trends do not differ by more than 0.1σ overall and more than 1σ in the individual sectors.

[58] An interesting aspect of the interannual variability of the seasonal changes is the tendency for periods of greater sea ice extents near the winter maxima to be associated with periods of lesser sea ice extents near the summer minima and vice versa. In addition, this phenomenon has a period of $3\text{--}5$ years and tends to vary in phase from sector to sector. The phase of the $3\text{--}5$ year periodic components of the interannual variability progresses from sector to sector from the Weddell Sea along East Antarctica but not consistently through to the Ross Sea sector and Bellingshausen/Amundsen Seas sector. The same effect is shown in Figure 23. While there is an association of the variations with the ACW on a sector-to-sector basis, the association is not as clear as in the more detailed analysis of extents in 1° longitudinal sectors by *Gloersen and Huang [1999]*.

[59] **Acknowledgments.** We greatly appreciate the help of John Eylander, Steve Fiegles, Mike Martino, and Jamila Saleh of Raytheon STX for their assistance in the processing of the data and the generation of the figures. We also appreciate the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, for providing the SSMI radiances. This work was supported by Polar Programs at NASA Headquarters and by NASA's Earth Observing System (EOS) program.

References

- Allison, I., The East Antarctic sea ice zone: Ice characteristics and drift, *Geo J.*, **18**, 103–115, 1989.
- Björge, E., O. M. Johannessen, and M. W. Miles, Analysis of merged SSMR-SSM/I time series of Arctic and Antarctic sea ice parameters 1978–1995, *Geophys. Res. Lett.*, **24**, 413–416, 1997.
- Bromwich, D., Z. Liu, M. L. Van Woert, and A. N. Rogers, Winter atmospheric forcing of the Ross Sea polynya, *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 101–133, AGU, Washington, D. C., 1998.
- Carleton, A. M., Antarctic sea-ice relationships with indices of the atmospheric circulation of the Southern Hemisphere, *Clim. Dyn.*, **3**, 207–220, 1989.