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Variability of Antarctic sea ice 1979–1998

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Abstract

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 ± 4190 km^2 yr^{-1} (0.98 ± 0.37% $(decade)^{-1}$). The increase in the area of sea ice within the extent boundary is similar (10,860 ± 3720 km^2 yr^{-1} and 1.26 ± 0.43% $(decade)^{-1}$). Regionally, the trends in extent are positive in the Weddel Sea (1.4 ± 0.9% $(decade)^{-1}$), Pacific Ocean (2.0 ± 1.4% $(decade)^{-1}$), and Ross (6.7 ± 1.1% $(decade)^{-1}$) sectors, slightly negative in the Indian Ocean (−1.0 ± 1.0% $(decade)^{-1}$), and strongly negative in the Bellingshausen-Amundsen Seas sector

(−9.7 ± 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.

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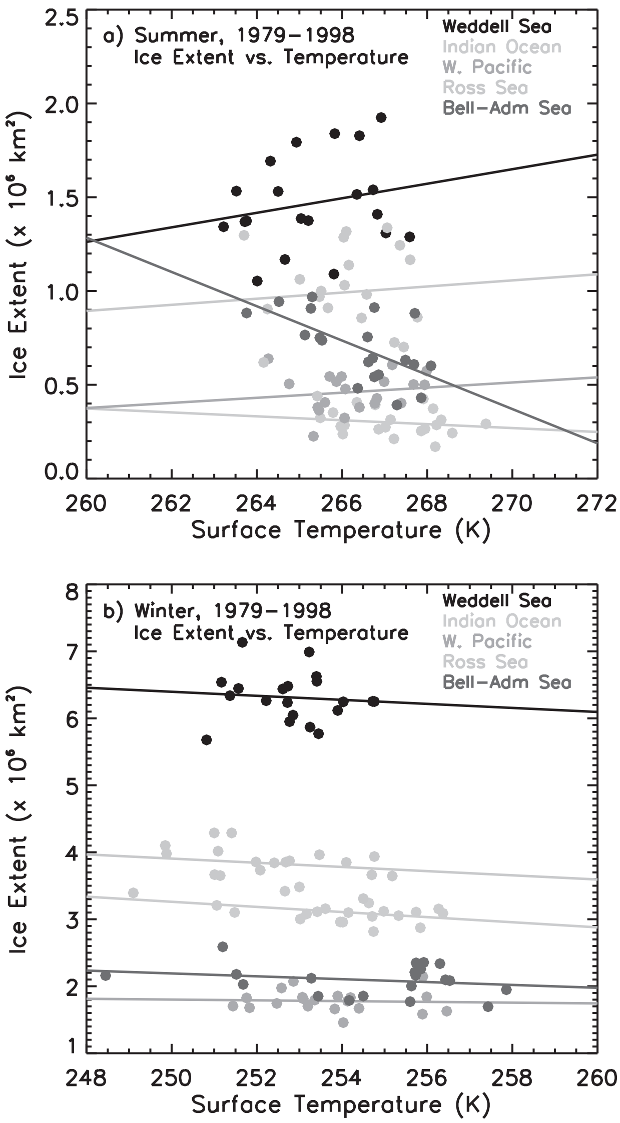

Figure 22. Relations between regionally averaged sea ice extents and regionally averaged surface temperatures over the ice pack as derived from satellite infrared for (a) summer month of January showing generally consistent relations from sector to sector and (b) winter month of July showing negative 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 different 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 ($\lesssim 0.08 \times 10^6$ km^2 peak to peak) is only ≈1/25 compared to the maximum interannual deviations in extent ($\lesssim 2 \times 10^6$ km^2 in Figures 3b–7b). The amplitudes of the QQ oscillations are also only ≈1/3 compared to the 3–5 cycles of interannual variability (amplitudes $\lesssim 0.26 \times 10^6$ 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 ± 4190 km^2 yr^{-1} (+0.98 ± 0.37% (decade)$^{-1}$) increase in sea ice extent and a very similar +10,860 ± 3720 km^2 yr^{-1} (+1.26 ± 0.43% (decade)$^{-1}$) increase in sea ice area. Regionally, the trends in extent are positive in the Weddell Sea (1.4 ± 0.9% (decade)$^{-1}$), Pacific Ocean (2.0 ± 1.4% (decade)$^{-1}$), and Ross Sea (6.7 ± 1.1% (decade)$^{-1}$) sectors, slightly negative in the Indian Ocean (−1.0 ± 1.0% (decade)$^{-1}$), and negative in the Bellingshausen/Amundsen Seas sector (−9.7 ± 1.5% (decade)$^{-1}$). An overall increase in Antarctic sea ice cover, during a period when global climate appears to have been warming by 0.2 K (decade)$^{-1}$ [*Hansen et al.*, 1999], stands in marked contrast to the observed decrease in the Arctic sea ice extent of −34,300 ± 3700 km^2 yr^{-1} (−2.8 ± 0.3% (decade)$^{-1}$) and sea ice area of −29,500 ± 3800 km^2 yr^{-1} (−2.8 ± 0.4% (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 ± 17,500 km^2 yr^{-1}) and percentage (+2.5 ± 1.8% (decade)$^{-1}$) and second largest in summer (+6700 ± 12,600 km^2 yr^{-1} and +1.7 ± 3.2% (decade)$^{-1}$) in terms of percentage change. The changes for the winter season (+7400 ± 8500 km^2 yr^{-1} and +0.4 ± 0.5% (decade)$^{-1}$) and for spring (+10,100 ± 14,000 km^2 yr^{-1} and +0.7 ± 1.0% (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-

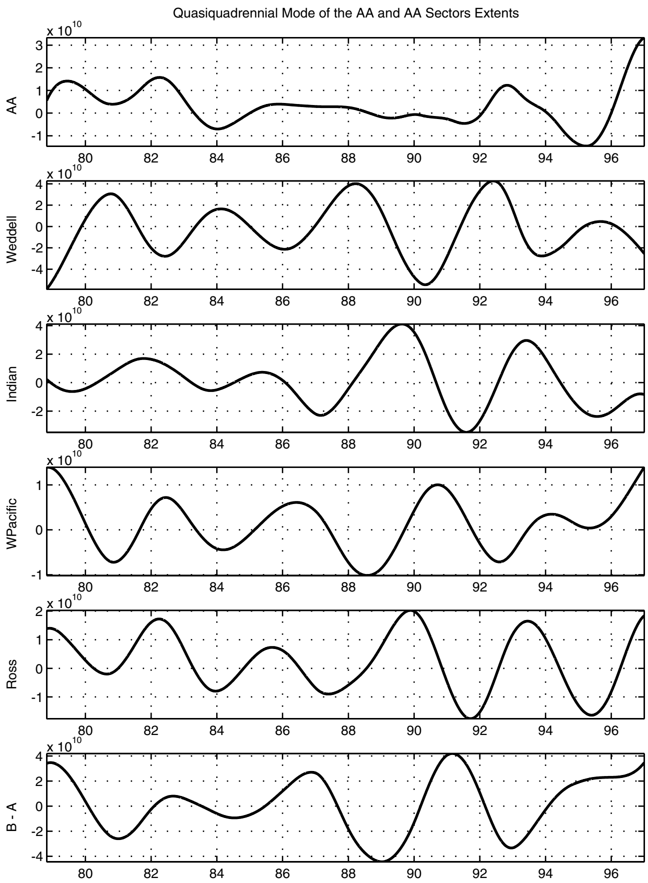

Figure 23. QQ modes of the sea ice concentration oscillations by regional sector. These QQ modes are obtained by summing over the regional sectors the results of the EMD of sea ice concentrations in 1° longitudinal sectors around the pole by *Gloersen and Huang* [1999]. See color version of this figure 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 ($-0.11 \pm 0.09 \times 10^6$ km^2 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 km or a meridional change of <0.1°, which is small compared to some previous estimates [e.g., *Parkinson and Bindschadler*, 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 6–9% 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 3–5 years, these represent only about 20–40% 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 3–5 years and tends to vary in phase from sector to sector. The phase of the 3–5 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].

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References

Allison, I., The East Antarctic sea ice zone: Ice characteristics and drift, *Geo J.*, *18*, 103–115, 1989.

Bjørgo, E., O. M. Johannessen, and M. W. Miles, Analysis of merged SSMR-SSMI 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.

Carsey, F. D., Microwave observation of the Weddell polynya, *Mon. Weather Rev.*, *108*, 2032–2044, 1980.
Cavalieri, D. J., and S. Martin, A passive microwave study of polynyas along the Antarctic Wilkes Land coast, in *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, volume 43, edited by S. Jacobs, pp. 227–252, AGU, Washington, D. C., 1985.
Cavalieri, D. J., and C. L. Parkinson, Large-scale variations in observed Antarctic sea ice extent and associated atmospheric circulation, *Mon. Weather Rev.*, *109*, 2323–2336, 1981.
Cavalieri, D. J., P. Gloersen, and W. J. Campbell, Determination of sea ice parameters with the Nimbus 7 SMMR, *J. Geophys. Res.*, *89*, 5355–5369, 1984.
Cavalieri, D. J., J. P. Crawford, M. R. Drinkwater, D. T. Eppler, L. D. Farmer, R. R. Jentz, and C. C. Wackerman, Aircraft active and passive microwave validation of sea ice concentration from the Defense Meteorological Satellite Program Special Sensor Microwave Imager, *J. Geophys. Res.*, *96*, 21,989–22,008, 1991.
Cavalieri, D. J., K. M. St. Germain, and C. T. Swift, Reduction of weather effects in the calculation of sea-ice concentration with the DMSP SSM/I, *J. Glaciol.*, *41*, 455–464, 1995.
Cavalieri, D. J., P. Gloersen, C. L. Parkinson, J. C. Comiso, and H. J. Zwally, Observed hemispheric asymmetry in global sea ice changes, *Science*, *278*, 1104–1106, 1997.
Cavalieri, D. J., C. L. Parkinson, P. Gloersen, J. C. Comiso, and H. J. Zwally, Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets, *J. Geophys. Res.*, *104*, 15,803–15,814, 1999.
Comiso, J. C., Characteristics of Arctic winter sea ice from satellite multispectral microwave observations, *J. Geophys. Res.*, *91*, 975–994, 1986.
Comiso, J. C., *SSM/I Sea Ice Concentrations Using the Bootstrap Algorithm*, *NASA Ref. Publ.*, *1380*, 49 pp., 1995.
Comiso, J. C., Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements, *J. Clim.*, *13*, 1674–1696, 2000.
Comiso, J. C., and A. L. Gordon, Cosmonaut polynya in the Southern Ocean: Structure and variability, *J. Geophys. Res.*, *101*, 18,297–18,313, 1996.
Comiso, J. C., and A. L. Gordon, Interannual variability in summer sea ice minimum, coastal polynyas and bottom water formation in the Weddell Sea, in *Antarctic Sea Ice. Physical Properties, Interactions, and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 293–315, AGU, Washington, D. C., 1998.
Comiso, J. C., D. J. Cavalieri, C. L. Parkinson, and P. Gloersen, Passive microwave algorithms for sea ice concentration: A comparison of two techniques, *Remote Sens. Environ.*, *60*, 357–384, 1997.
Deacon, G. E. R., The hydrology of the Southern Ocean, *Discovery Rep.*, *15*, 1–124, 1937.
Draper, N. R. and H. Smith, *Applied Regression Analysis*, 2nd ed., 709 pp., John Wiley, New York, 1981.
Enomoto, H., S.-F. Tian, and T. Yamanouchi, Interannual fluctuations of sea ice extent in the Antarctic and associated atmospheric conditions, paper presented at NIPR Symposium or Polar Meteorology Glaciology, Nat. Inst. of Polar Res., Tokyo, 1992.
Fahrbach, E., G. Rohardt, N. Scheele, M. Schröder, V. Strass, and A. Wisotzki, Formation and discharge of deep and bottom water in the northwestern Weddell Sea, *J. Mar. Res.*, *53*, 515–538, 1995.
Foster, T. D., and J. H. Middleton, Variability in the bottom water of the Weddell Sea, *Deep Sea Res., Part A*, *26*, 743–762, 1979.
Gloersen, P., and W. J. Campbell, Recent variations in Arctic and Antarctic sea-ice covers, *Nature*, *352*, 33–36, 1991.
Gloersen, P., and D. J. Cavalieri, Reduction of weather effects in the calculation of sea ice concentration from microwave radiances, *J. Geophys. Res.*, *91*, 3913–3919, 1986.
Gloersen, P., and N. E. Huang, In search of an elusive Antarctic circumpolar wave in sea ice extents: 1978-1996, *Polar Res.*, *18*, 167–173, 1999.
Gloersen, P., and A. Mernicky, Oscillatory behavior in Antarctic sea ice concentrations, in *Antarctic Sea Ice: Physical Processes, Interactions, and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 161–171, AGU, Washington, D. C., 1998.
Gloersen, P., and W. B. White, Reestablishing the circumpolar wave in sea ice around Antarctica from one winter to the next, *J. Geophys. Res.*, *106*, 4391–4395, 2001.
Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally, Arctic and Antarctic sea ice, 1978–1987: Satellite passive-microwave observations and analysis, *NASA Spec. Publ.*, *511*, 290 pp., 1992.
Gloersen, P., C. L. Parkinson, D. J. Cavalieri, J. C. Comiso, and H. J. Zwally, Spatial distribution of trends and seasonality in the hemispheric sea ice covers: 1978-1996, *J. Geophys. Res.*, *104*, 20,827–20,835, 1999.
Gordon, A. L., and J. C. Comiso, Polynyas in the Southern Oceans, *Sci. Am.*, *256*, 90–97, 1988.
Gordon, A. L., B. A. Huber, H. H. Hellmer, and A. Ffield, Deep and bottom water of the Weddell Sea's western rim, *Science*, *262*, 95–97, 1993.
Gordon, H. B., and S. P. O'Farrell, Transient climate change in the CSIRO coupled model with dynamic sea ice, *Mon. Weather Rev.*, *125*, 875–907, 1997.
Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, GISS analysis of surface temperature change, *J. Geophys. Res.*, *104*, 30,997–31,022, 1999.
Huang, N. E., Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N.-C. Yen, C. C. Tung, and H. H. Liu, The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis, *Proc. R. Soc. London, Ser. A*, *454*, 903–995, 1998.
Jacka, T. H., and W. F. Budd, Detection of temperature and sea ice extent changes in the Antarctic and Southern Ocean, in *International Conference on the Role of the Polar Regions in Global Change*, vol. 1, edited by G. Weller, C. L. Wilson, and B. A. B. Severin, pp. 63–70, Geophys. Inst., Univ. Alaska, Fairbanks, 1991.
Jacobs, S. S., and J. C. Comiso, A recent sea-ice retreat west of the Antarctic Peninsula, *Geophys. Res. Lett.*, *20*, 1171–1174, 1993.
Jacobs, S. S., and J. C. Comiso, Climate variability in the Amundsen and Bellingshausen Seas, *J. Clim.*, *10*, 697–709, 1997.
Johannessen, O. M., M. Miles, and E. Bjørgo, The Arctic's shrinking sea ice, *Nature*, *376*, 126–127, 1995.
King, J. C., Recent climate variability in the vicinity of the Antarctic Peninsula, *Int. J. Climatol.*, *14*, 357–369, 1994.
Kukla, G. J., Recent changes in snow and ice, in *Climatic Change*, edited by J. Gribbin, pp. 114–129, Cambridge Univ. Press, New York, 1978.
Kukla, G., and J. Gavin, Summer ice and carbon dioxide, *Science*, *214*, 497–503, 1981.
Kuo, C., C. Lindberg, and D. J. Thomson, Coherence established between atmospheric carbon dioxide and global temperature, *Nature*, *343*, 709–714, 1990.
Lange, M. A., S. F. Ackley, P. Wadhams, G. S. Dieckmann, and H. Eicken, Development of sea ice in the Weddell Sea, *Ann. Glaciol.*, *12*, 92–96, 1989.
Lindberg, C. R., Multiple taper spectral analysis of terrestrial free oscillations, Ph.D. thesis, Univ. of Calif., San Diego, 1986.
Lindberg, C. R., and J. Park, Multiple-taper spectral analysis of terrestrial free oscillations, part II, *Geophys. J. R. Astron. Soc.*, *91*, 795–836, 1987.
Manabe, S., M. J. Spelman, and R. J. Stouffer, Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2, part II, Seasonal response, *J. Clim.*, *5*, 105–126, 1992.
Martinson, D. G., P. D. Killworth, and A. L. Gordon, A convective model for the Weddell Polynya, *J. Phys. Oceanogr.*, *11*, 466–488, 1981.
National Snow and Ice Data Center (NSIDC), DMSP SSM/I brightness temperatures and sea ice concentration grids for the polar regions on CD-ROM user's guide, Spec. Rep. 1, Coop. Inst. for Res. in Environ. Sci., Univ. of Colo., Boulder, 1992.
Parkinson, C. L., On the development and cause of the Weddell polynya in a sea ice simulation, *J. Phys. Oceanogr.*, *13*, 501–511, 1983.
Parkinson, C. L., Spatial patterns in the length of the sea ice season in the Southern Ocean, 1979-1986, *J. Geophys. Res.*, *99*, 16,327–16,339, 1994.
Parkinson, C. L., Length of the sea ice season in the southern ocean, 19887–1994, in *Antarctic Sea Ice, Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 173–186, AGU, Washington, D. C., 1998.
Parkinson, C. L., and R. A. Bindschadler, Response of Antarctic sea ice to uniform atmospheric temperature increases, in *Climate Processes and Climate Sensitivity*, *Geophys. Monogr. Ser.*, vol. 29, edited by J. E. Hansen, and T. Takahashi, pp. 254–264, AGU, Washington, D. C., 1984.
Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso, Arctic sea ice extents, areas, and trends, 1978–1996, *J. Geophys. Res.*, *104*, 20,837–20,856, 1999.
Raper, S. C. B., T. M. L. Wigley, P. R. Mayes, P. D. Jones, and M. J. Salinger, Variations in surface air temperatures, part 3, The Antarctic, 1957-82, *Mon. Weather Rev.*, *112*, 1341–1353, 1984.
Rintoul, S. R., On the origin and influence of Adélie Land bottom water, in *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. 151–171, Washington, D. C., 1998.
Stammerjohn, S. E., and R. C. Smith, Opposing southern ocean climate patterns as revealed by trends in regional sea ice coverage, *Clim. Change*, *37*, 617–639, 1997.
Steffen, K., J. Key, D. J. Cavalieri, J. Comiso, P. Gloersen, K. St. Germain, and I. Rubinstein, The estimation of geophysical parameters using passive microwave algorithms, in *Microwave Remote Sensing of Sea Ice*, *Geophys. Monogr. Ser.*, vol. 68, edited by F. Carsey, pp. 201–231, Washington, D. C., 1992.
Takizawa, T., K. I. Ohshima, S. Ushio, T. Kawamura, and H. Enomoto, Temperature structure and characteristics appearing on SSM/I images of the Cosmonaut Sea, Antarctica, *Ann. Glaciol.*, *20*, 298–306, 1994.