GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 8, PAGES 1595-1598, APRIL 15, 2001

Anomalous peak in Antarctic sea-ice area, winter 1998, coincident with ENSO

Edward Hanna

Institute of Marine Studies, University of Plymouth, Plymouth, UK

Abstract. The results of an updated satellite analysis of hemispheric and regional Antarctic sea-ice cover are presented based on October 1987-September 1999 Special Sensor Microwave/Imager (SSM/I) data. These show an ongoing slight but significant hemispheric increase of 3.7(±0.3)% in extent and 6.6(±1.5)% in area. In the two principal sectors, Weddell Sea ice extent (area) decreased by 3.4(±1.0) (3.9(±4.6)) % and Ross Sea ice extent (area) increased by 10.9(±1.0) (18.3(±4.6)) %. Hemispheric, Ross Sea and Western Pacific Ocean ice peaks in September 1998 were anomalously high, and may have been related to atmospheric and oceanic anomalies in the Pacific Ocean and beyond associated with that year's exceptionally strong ENSO. Preliminary comparison of Antarctic sea-ice-concentration data with European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses fields suggests that the unusually extensive sea ice in winter 1998 was concomitant with an equatorward shift of the circumpolar westerly surface winds over the southern Pacific Ocean.

1. A New, Updated Antarctic Sea-ice Record

Passive microwave (PM) satellites provide the only wholly comprehensive spatial and temporal monitoring of Antarctic sea-ice – a fully coupled component of global climate that lacks adequate representation in climate models (Hanna 1996). Existing published series (Cavalieri et al. 1997, Bjørgo et al. 1997) consider data only to December 1996 and August 1995 respectively. Because of the potential sensitivity of the sea-ice cover to changing atmospheric, oceanic and climatic conditions, the construction and analysis of a more recent record is warranted. The Bristol sea-ice concentration algorithm (Smith 1996) – an improved version of the Bootstrap algorithm (Comiso 1995) - was used to construct a new Antarctic sea-ice series that is arguably more systematic than existing published series (Hanna and Bamber 2001). Key factors expected to favour the new series are (1) the more thorough tuning of brightness temperature tie points, and (2) an automatic algorithm developed and incorporated to remove residual noise in PM satellite images. Some preliminary results of the Bristol method, spanning August 1987-September 1997, were presented (Hanna 1999).

Here the latest available National Snow and Ice Data Center (NSIDC) Defense Meteorological Satellite Program (DMSP) F13 SSM/I Brightness Temperature Grids for the Polar Regions data were used to update the series to the period October 1987-September 1999 (Fig. 1). The main aim was to search for significant hemispheric and regional coverage trends in an attempt to elucidate ongoing Antarctic and global climatic change. Least squares regression analysis showed that Antarctic (hemispheric) sea ice extent increased by 3.7(±0.3)% and area by 6.6(±1.5)% (annual means of monthly trends). Sea-ice extent is the aggregate area of image pixels containing ≥15% sea-ice, while sea-ice area is the area actually covered by sea-ice in pixels of ≥15% concentration, i.e. extent times concentration for all such pixels. Because area increased faster than extent, the ice became slightly more consolidated, with mean concentration increasing by 2.8(±1.7)%. Error estimates are based on a tie-point sensitivity study and temporal random error and spatial error analysis (Hanna 1998). These results suggest that the rather smaller increase of 1.0(±0.5)% per decade in Antarctic sea-ice extent and 1.3(±0.6)% in area detected for the period November 1978-December 1996 (Cavalieri et al. 1997) is ongoing. This increase was apparently greater from 1987-96 (see Fig. 2B in Cavalieri et al. 1997), and also for the more recent (1987-99) period considered here. Watkins and Simmonds (2000) similarly noted positive and statistically significant increases in Antarctic sea-ice extent and area, based on 1987-96 data and concentrated in the mid-1990s.

Most of the positive sea-ice trends occurred from March-October (i.e. Southern autumn/winter), peaking in April (9.0% in extent and 18.9% in area). In September, the month of maximum coverage, hemispheric extent (area) grew by 5.8(9.9)%. Part of the upward trend can be attributed to a jump in sea-ice coverage in 1998 compared with previous years. September 1998 extent (area) was 2.7 (3.0) standard deviations (SDs) above the 1988-99 September mean, and therefore statistically anomalous at the 5% significance level (Table 1). This anomalously high Antarctic sea-ice coverage was particularly pronounced in the Ross Sea and W Pacific Ocean areas (Fig. 2). However, ice coverage was 'normal' again the following winter (1999). Removing the 1998 value from the September set of hemispheric figures still leaves upward trends for Antarctic sea-ice extent (area) of 3.1 (4.0)%.

Conversely, November-February (Southern summer) had small or negative trends, with the most notable decreases in December (3.6% in extent and 6.9% in area). In February, the month of minimum Antarctic sea-ice coverage, there was relatively little net change, but since there is so little ice in summer anyway, the percentage changes are not notable. Therefore there has been an increase in seasonality of the ice, primarily seen as greater autumn and winter coverage, during these twelve years.

2. Unusually Large Pacific Ocean Ice Cover in Winter 1998

We refer to the Antarctic regional sectors used in Gloersen et al. (1992) (Fig. 2). Standard error estimates are of the order of

Paper number 2000GL012368.
0094-8276/01/2000GL012368$05.00

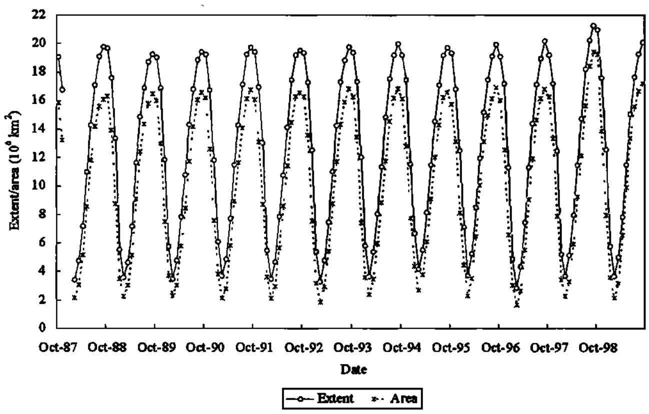

Figure 1. Monthly Antarctic sea-ice extent and area, October 1987-September 1999.

±1.0% for trends in extent and ±4.6% for trends in area for the sectors; errors might be greater than this, but ill-defined, for the summer months of February and March - especially in the Weddell Sea where some meltponding occurs (Hanna 1998).

The increase in Antarctic sea-ice extent and area over the study period was concentrated in the three sectors straddling the Pacific Ocean (W Pacific Ocean, Ross Sea and Bellingshausen/Amundsen Seas) (Table 1). The largest September (ice maximum month) increases were also in these sectors. Weddell Sea ice overall decreased slightly, with only a marginal decrease in extent for September. Bellingshausen/Amundsen Seas' ice became much more seasonal (more extensive in winter, less so in summer).

The unusually extensive Antarctic sea-ice in September 1998, split by sector, was anomalous only in the Ross Sea (extent and area) and the W Pacific Ocean (area only). These anomalies, while still significant at the 5% level, are not so striking as the hemispheric one for the same month, due to much greater interannual fluctuations in regional ice coverage (Fig. 3) (successive hemispheric winter ice maxima were remarkably constant).

It is curious that the months of greatest negative (greatest positive) sea-ice extent and area trends in the Weddell Sea coincided with those of greatest positive (least positive) trends in the Ross Sea (Fig. 4). These two sectors are geographically situated almost opposite each other and contain the bulk of Antarctic sea-ice. Contrasting trends in regional sea-ice coverage were also noted based on earlier, 1978-95, data (Stammerjohn and Smith 1997). In the present study, the largest overall sea-ice increases were in the Western Pacific Ocean and Ross Sea, while the largest decreases (albeit much more modest than the increases) were in the Weddell Sea and (to a lesser extent) Indian Ocean. Again, these two pairs of adjoining sectors are almost opposite. The near-antiphase relations in the trends and timings of their respective coverages are possibly signatures of the Antarctic Circumpolar Wave (ACW) - a coupled anomaly of significant variations in sea-level pressure, mean wind stress, sea-surface temperature and sea-ice extent that propagates eastwards around Antarctica in 8-10 years (White and Peterson 1996). The ACW has a 4-5-year period due to its double waveform. The hemispheric data largely mask its effect: hence the much smaller hemispheric trends.

3. Implications

In contrast to Arctic sea-ice, which has recently shown marked losses (Johannessen et al. 1999, Parkinson et al. 1999, Vinnikov et al. 1999), Antarctic sea ice coverage has increased slightly but significantly since the start of the continuous passive microwave satellite record (1978). This is consistent with cooling over Antarctica from 1979-98 (Comiso 2000).

Atmospheric and oceanic anomalies accompanying the exceptionally strong ENSO of 1998 (Slingo 1998) may explain the unusually extensive sea ice in winter 1998, particularly as the anomalous ice was concentrated in the sectors adjoining the Pacific Ocean. A natural extension of this research will be to cross-correlate climate analysis fields (especially from the forthcoming 'second generation' ECMWF reanalysis, ERA-40 (Simmons and Gibson 2000)) with ice-concentration data to search for teleconnections and explore possible mechanisms for climate/ice couplings. Yuan and Martinson (2000) found that up to 34% of the variance in spatially averaged, detrended Antarctic sea-ice extent anomalies is linearly related to ENSO, and revealed a significant meridional component between Antarctic sea-ice extent and extrapolar climate/sea-surface temperatures.

Table 1. October 1987-September 1999 percentage trends in Antarctic (hemisphere and sectors) sea-ice extent (E) and area (A) for all months and February (ice minimum month) and September (ice maximum month) values only. Antarctic sea-ice E & A anomalies for September 1998 are shown as standard deviations above the corresponding September 1988-99 means.

Region		All months %	February %	September %	September 1998 anomaly (SD)
Hemisphere	E	3.7	2.7	5.8	2.7
	A	6.6	-1.8	9.9	3.0
Weddell Sea	E	-3.4	-7.7	-1.7	0.6
	A	-3.9	-14.1	0.1	1.5
Indian Ocean	E	1.9	4.1	-2.6	0.1
	A	3.5	-3.8	0.8	1.5
W Pacific Ocean	E	17.1	25.7	23.8	1.6
	A	30.7	41.6	40.6	2.4
Ross Sea	E	10.9	13.3	12.6	2.0
	A	18.3	18.8	18.1	2.2
Bellingshausen/Amundsen Seas	E	5.1	-6.1	18.5	0.5
	A	8.9	-21.2	23.1	1.1

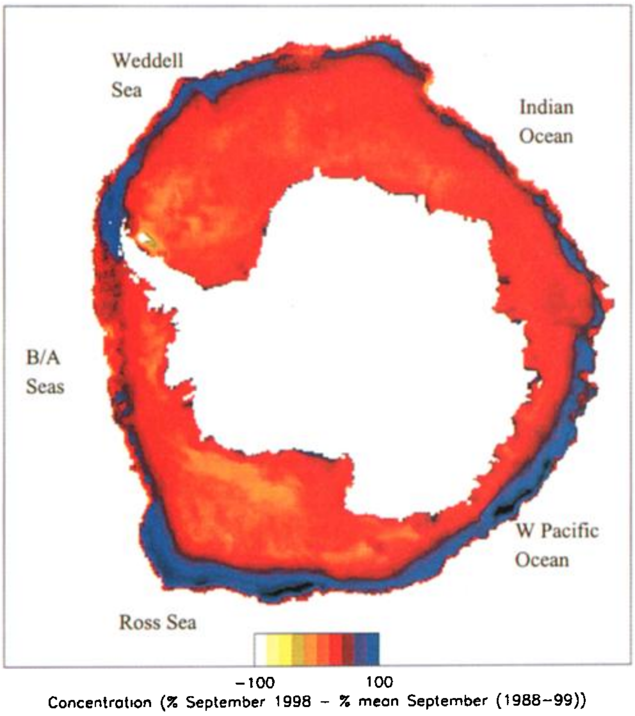

Figure 2. Antarctic sea-ice concentration anomaly image for September 1998, relative to mean September (1988-99) conditions.

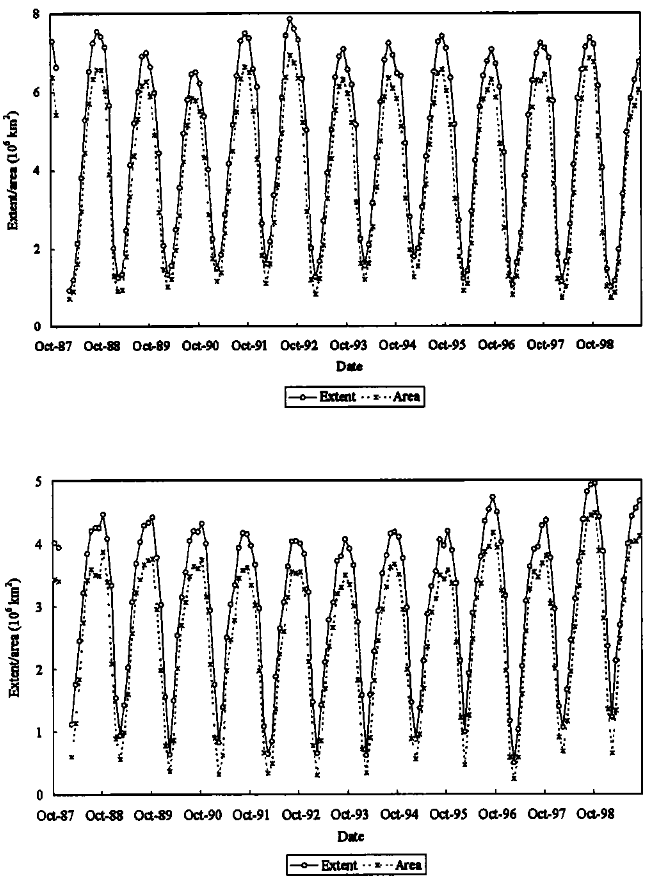

Figure 3. Monthly sea ice extent and area, October 1987-September 1999, for (a) Weddell Sea and (b) Ross Sea.

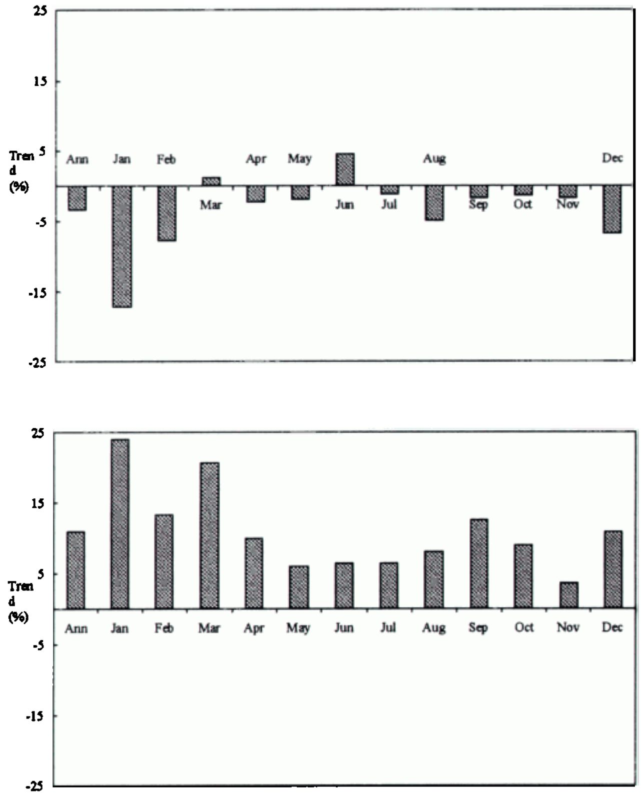

Figure 4. Annual and monthly trends in sea-ice extent for (a) Weddell and (b) Ross Seas. Area trends (not shown) have similar patterns.

Perhaps abnormally strong ENSO conditions in 1998 shifted the circumpolar westerly winds (and Antarctic Circumpolar Current?) equatorward, especially in the Antarctic regions adjacent to the Pacific Ocean, allowing winter ice growth that year to also extend unusually far north. This hypothesis is supported by a modelling study in which the circumpolar trough moved closer to Antarctica in response to sea-ice removal (Bromwich et al. 1998).

Sea-ice-concentration data were compared with surface wind fields from ECMWF operational analyses (Berrisford et al. 1998) for Septembers in the study period. This revealed an equatorward shift (not shown) of the circumpolar westerly surface (10-m) winds over the high-latitude southern Pacific by several degrees in September 1998 relative to September 1997 and mean September (1988-98) conditions. The inner margin of the circumpolar westerlies was at ~63-65°S in September 1998 map and at ~65-68°S in the mean September map. These surface wind fields are constrained by observations as well as model parameters (e.g. scatterometer, ships and drifting buoys). Although there were some model changes over time, there were no significant overall differences in the mean monthly southern Pacific sea-ice limits imposed in the model for these Septembers, and the meridional wind shift is considered real (F. Lalaurette, pers. comm., 2001).

It is unclear for how long the recent comparative stability in hemispheric (compared with regional) Antarctic sea-ice coverage will continue in the light of climatic change/anthropogenic global warming and possibly associated ENSO changes (Federov and Philander 1999, Timmermann et al. 1999, Urban et al. 2000). The myriad potential climatic feedbacks makes it extremely difficult to determine their net effect but thermal inertia and changes in vertical mixing of the high-latitude Southern Ocean might well delay the likely response (an eventual melt (Wu et al. 1999)) of the Antarctic sea-ice cover (Hanna 1996). Moreover, Southern Extratropic Twentieth Century global warming so far seems to have been somewhat muted compared with that in the Northern Extratropics and Tropics (Bell et al. 1999). In Antarctica, this may be due to a decadal weakening of the semiannual oscillation (the twice-yearly contraction/expansion of the southern circumpolar trough) restricting meridional heat exchange between Antarctica and its environs (van den Broeke 2000).

Apart from concerns about future climatic change, there are suggestions from whaling records of a reduction in Antarctic sea-ice cover in the 1960s much larger than changes so far seen in the hemispheric satellite record (de la Mare 1997). Ongoing, improved satellite monitoring and accurate data evaluation will likely prove paramount for providing early warning of possible perturbations to the (currently hemispherically stable) Antarctic sea-ice system.

Acknowledgements. Two anonymous reviewers provided invaluable suggestions, which helped improve the paper. DMSP-F8, -F11 and -F13 Brightness Temperatures 1988 through 1999, were obtained from the EOSDIS NSIDC Distributed Active Archive Center (NSIDC DAAC), University of Colorado at Boulder, USA. Dr. Paul Berrisford (Univ. Reading) helped retrieve ECMWF data, and Dr. François Lalaurette (Head, Meteorological Operations Section, ECMWF) gave useful advice on the ECMWF analyses' wind fields and sea-ice treatment.

References

Bell, G.D., M.S. Halpert, C.F. Ropelewski, V.E. Kousky, A.V. Douglas, R.C. Schnell, and M.E. Gelman, Climate assessment for 1998, Bull. Amer. Meteor. Soc., 80 (5), S1-S48, 1999.

Berrisford, P., R. Brugge, D. Li, and L. Steenman-Clark, Diagnosis of the ECMWF Re-Analysis dataset by the Centre for Global Atmospheric Modelling, UGAMP Technical Report No. 48, CGAM, University of Reading, Reading, UK, 1998.

Bjørgo, E., O.M. Johannessen, and M.W. Miles, Analysis of merged SMMR-SSMI time series of Arctic and Antarctic sea ice parameters 1978-1995, Geophys. Res. Lett., 24, 413-416, 1997.

Bromwich, D.H., B. Chen, and K.M. Hines, Global atmospheric impacts induced by year-round open water adjacent to Antarctica, J. Geophys. Res., 103, 11173-11189, 1998.

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.

Comiso, J.C., SSM/I Sea Ice Concentrations Using the Bootstrap Algorithm, NASA Reference Publication 1380, National Aeronautics and Space Administration, 1995.

Comiso, J.C., Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements. J. Climate 13, 1674-1696, 2000.

De la Mare, W.K., Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records, Nature, 389, 57-60, 1997.

Federov, A.V., and S.G. Philander, Is El Nino changing?, Science, 288, 1997-2002, 2000.

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 Special Publication NASA SP-511, National Aeronautics and Space Administration, 1992.

Hanna, E., The role of Antarctic sea ice in global climate change, Prog. Phys. Geogr., 20, 371-401, 1996.

Hanna, E., Observations of Antarctic Sea Ice from Satellite Data, and Climatic Couplings, Ph.D. Thesis, University of Bristol, Bristol, UK, 1998.

Hanna, E., Recent observations of Antarctic sea-ice. Weather, 54, 71-87, 1999.

Hanna, E. and J. Bamber, Derivation and optimization of a new Antarctic sea-ice record. Int. J. Remote Sensing, 22, 113-139, 2001.

Johannessen, O.M, E.V. Shalina and M.W. Miles, Satellite evidence for an Arctic sea ice cover in transformation, Science, 286, 1937-1939, 1999.

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, 20837, 1999.

Simmons, A.J., and J.K. Gibson, ERA-40 Project Report Series 1. The ERA-40 Project Plan, European Centre for Medium-Range Weather Forecasts, Reading, UK, 2000.

Slingo, J., The 1997/98 El Niño, Weather, 53, 274-281, 1998.

Smith, D.M., Extraction of winter total sea-ice concentration in the Greenland and Barents Seas from SSM/I data, Int. J. Remote Sensing, 17, 2625-2646, 1996.

Stammerjohn, S.E., and R.C. Smith, Opposing Southern Ocean climate patterns as revealed by trends in regional sea-ice coverage, Climatic Change, 37, 617-639, 1997.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, Increased El Nino frequency in a climate model forced by future greenhouse warming, Nature, 398, 694-697, 1999.

Urban, F.E., J.E. Cole, and J.T. Overpeck, Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record, Nature, 407, 989-993, 2000.

Van den Broeke, M.R., On the interpretation of Antarctic temperature trends, J. Climate, 13, 3885-3889, 2000.

Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett and V.F. Zakharov, Global warming and Northern Hemisphere sea ice extent, Science, 286, 1934-1937, 1999.

Watkins, A.B. and I. Simmonds, Current trends in Antarctic sea ice: the 1990s impact on a short climatology, J. Climate, 13, 4441-4451, 2000.

White, W.B., and R.G. Peterson, An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent, Nature, 380, 699-702, 1996.

Wu, X., W.F. Budd, and T.H. Jacka, Simulations of Southern Hemisphere warming and Antarctic sea-ice changes using global climate models, Ann. Glaciol., 29, 61-65, 1999.

Yuan, X., and D.G. Martinson, Antarctic sea ice extent variability and its global connectivity, J. Climate, 13, 1697-1717, 2000.

E. Hanna, Institute of Marine Studies, University of Plymouth, Drake Circus, Plymouth, Devon, PL4 8AA, UK (e-mail: E.Hanna@plymouth.ac.uk)

(Received September 15, 2000; accepted January 2, 2001.)