Anomalous atmospheric circulation over the Weddell Sea, Antarctica during the Austral summer of 2001/02 resulting in extreme sea ice conditions

John Turner, Stephen A. Harangozo, Gareth J. Marshall, John C. King, and Steve R. Colwell

British Antarctic Survey, National Environment Research Council, Cambridge, UK

Received 29 May 2002; revised 5 July 2002; accepted 16 July 2002; published 19 December 2002.

[1] During the Austral summer of 2001/02 exceptionally heavy sea ice conditions were experienced over the eastern Weddell Sea. Satellite microwave imagery showed that large negative (positive) ice anomalies were present from October 2001 to January 2002 over the north-western Weddell Sea (off the coast of Dronning Maud Land). These were a result of anomalously high (low) atmospheric pressure over the South Atlantic (southern Weddell Sea and Bellingshausen Sea), which gave strong north to north-westerly cyclonic flow over the northern and eastern Weddell Sea. This resulted in convergence of sea ice into the southern Weddell Sea and inhibited ice advection along the coast of Dronning Maud land. The atmospheric anomalies around the Weddell Sea were part of an Antarctic-wide amplification of the mean wavenumber 3 pattern resulting in more intrusions of mid-latitude air into the interior of the continent, giving rise to near-record warm temperatures at several locations. *INDEX TERMS:* 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology. **Citation:** Turner, J., S. A. Harangozo, G. J. Marshall, J. C. King, and S. R. Colwell, Anomalous atmospheric circulation over the Weddell Sea, Antarctica during the Austral summer of 2001/02 resulting in extreme sea ice conditions, *Geophys. Res. Lett.*, *29*(24), 2160, doi:10.1029/2002GL015565, 2002.

1. Background

[2] The Weddell Sea has the largest amount of multi-year sea ice in the Antarctic [*Gloersen et al.*, 1992] as a result of the impediment that the Antarctic Peninsula presents to the westward movement of ice in the coastal region. The climatological low pressure over the Weddell Sea, coupled with the cyclonic oceanic gyre, produces extensive multi-year ice to the east of the Peninsula, but results in little summer (DJF) season ice over the eastern Weddell Sea. For this reason, a number of research stations have been built along the coast of Dronning Maud Land since the International Geophysical Year (IGY) of 1957/58. Each year, Halley Station (75.5°S, 26.4°W) (see Figure 1) is relieved by ship during December, with the vessel usually reaching the station by following the coastal lead off Dronning Maud Land. During the 2001/02 Antarctic season, it proved impossible to reach Halley by ship because of extensive sea ice along the coast, and especially around the Stancomb Wills Ice Tongue east of the station. Despite the fact that the Weddell Sea, and in particular the area just to the east of the Peninsula, has some of the largest spatial variability of average summer sea ice in the Antarctic [*Parkinson*, 1992], this was the first time that it had proved impossible to relieve the station by ship since IGY. December is usually a time of rapid melting of the sea ice over the eastern Weddell Sea with the development of a coastal lead, but during 2001 this failed to materialise.

[3] In this paper we show that the anomalous sea ice conditions were created by a long-lived atmospheric blocking episode over the South Atlantic, coupled with anomalously low surface pressure over the southern Weddell and Bellingshausen Seas, which caused a build up of ice over the southern Weddell Sea and along the coast of Dronning Maud Land.

2. Satellite Observations of the Sea Ice

[4] Daily and monthly mean charts of sea ice extent and concentration from the Danish Center for Remote Sensing and the NOAA Ocean Modelling Branch were examined from January 2001 to February 2002, to determine the development and evolution of the ice anomalies. In the period up to September 2001, which is typically the time of ice growth towards maximum extent, the ice conditions in the Weddell Sea were unremarkable. In the early part of the year there had been more extensive ice than usual over the western Weddell Sea, but by August there was a very small negative anomaly at the tip of the Peninsula. Throughout September the negative anomaly to the east of the tip of the Peninsula extended further east, with positive anomalies becoming established east of 45°W. Over October to December the negative anomalies extended eastwards across the northern Weddell Sea, with the smallest extent of sea ice for this period since the satellite record of sea ice began in the early 1970s being observed over the longitude range 40–45°W (charts of the monthly mean sea ice concentration anomalies for October 2001 to January 2002 are shown in Figure 1, with all sea ice anomalies shown being differences from the 1979–97 means).

[5] As well as the large negative anomalies just described, there was also higher ice concentrations than usual off the coast of Dronning Maud Land (the long term mean ice concentration chart for December is shown in Figure 2). This anomaly began to develop during November, initially starting along the northern part of the Dronning Maud Land

0094-8276/02/2002GL015565

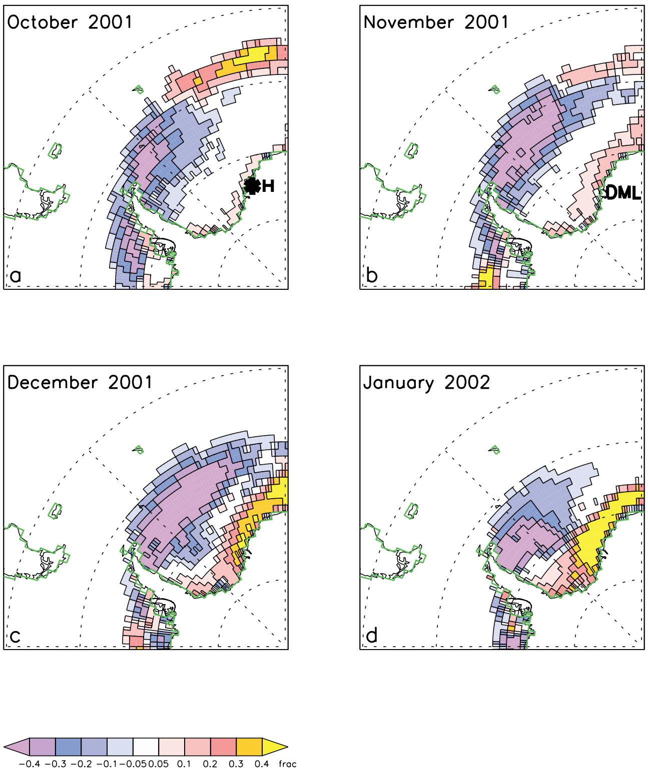

Figure 1. Monthly mean sea ice concentration anomalies (from the 1979–97 means) for the period October 2001 to January 2002. The scale shows the concentration anomalies in tenths. H denotes the location of Halley Station. DML indicates Dronning Maud Land.

coast and then extending south-westwards during December towards the Ronne-Filchner Ice Shelf.

3. Atmospheric Circulation Anomalies and the Impact on the Sea Ice

[6] The Weddell Sea is at the latitude of the circumpolar trough and is dominated throughout the year by a broadly cyclonic circulation of climatological easterly flow along the coast of Dronning Maud Land, southerly winds on the eastern side of the Peninsula in the form of a barrier wind and westerly flow along the northern Weddell Sea [*King and Turner*, 1997]. During 2001 the atmospheric circulation anomalies over the South Atlantic and Weddell Sea had been rather variable up to September, but from October (typically the start of the Antarctic ice-retreat season) became markedly anticyclonic (cyclonic) over the South Atlantic (Bellingshausen and Weddell Seas). Figure 3 shows the normalised mean sea level pressure (MSLP) anomaly of the October–December 2001 period (differenced from the mean for 1971–2000). The data were derived from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis (hereinafter written as NNR). This has marked spurious negative trends in MSLP at southern high latitudes due to considerable errors prior to the late 1960s but in general improves significantly thereafter [*Hines et al.*, 2000; *Marshall and Harangozo*, 2000].

[7] Figure 3 indicates that the largest positive MSLP anomaly across the Southern Hemisphere for the October to December period was located just north of South Georgia (54.5°S, 37.0°W) and was more than 4 SD away from the mean. This was coupled with lower than normal MSLP over the Bellingshausen and Weddell Seas, which created a much deeper than normal circumpolar trough from the Amundsen to the Weddell Sea. The negative MSLP anomalies on either side of the Peninsula were quite different from the norm, which consists of the "Antarctic Dipole" reported by *Yuan and Martinson* [2001]. The exceptional nature of these anomalies was apparent from the October to December mean MSLP from South Georgia and Halley station. There is a continuous surface meteorological record from 1906 to 1982 for South Georgia, but then a gap until an automatic weather station was installed on Bird Island in 2000. Unfortunately, the data for November 2000 are missing so that the mean for October to November 2001 is the only post-1982 data available for our analysis. However, the MSLP of over 1005 hPa during October to December 2001 was the highest recorded in the whole record, which occurred in parallel with the lowest pressure recorded at Halley since the station was established in 1957. The net effect of these MSLP anomalies was to increase the surface pressure gradient between South Georgia and the Antarctic Peninsula, giving predominantly north-westerly flow across the northern and north-eastern Weddell Sea.

[8] Over October to December 2001 there were small, but significant differences in the atmospheric circulation anomalies between months that had an impact on the sea ice conditions in the Weddell Sea. During October, surface pressure was quite low across both the Bellingshausen and Weddell Seas so that the resultant north-westerly flow was smaller than during the following two months. This resulted in smaller negative ice anomalies to the east of the tip of the Antarctic Peninsula (Figure 1a). Across the northern Weddell Sea there was also strong westerly flow,

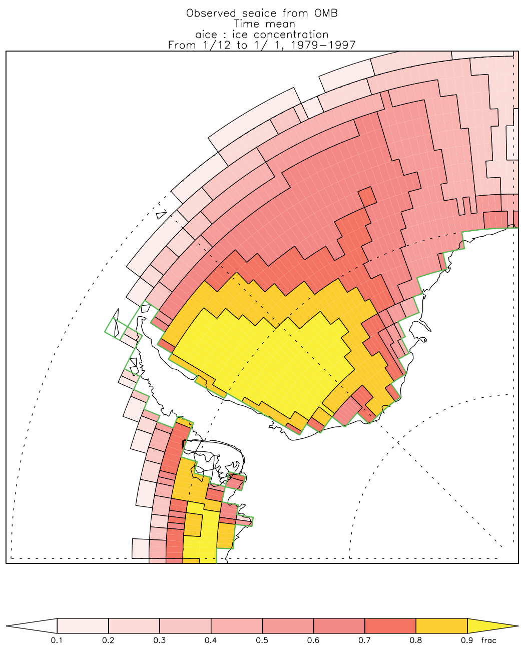

Figure 2. The mean December ice concentration fraction for 1979–97 as produced by the NOAA Ocean Modelling Branch.

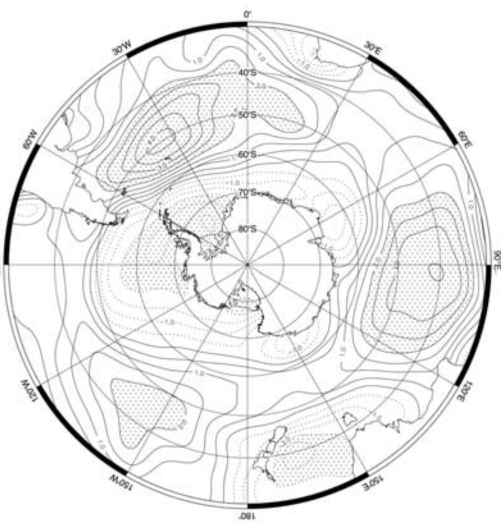

Figure 3. The normalised mean sea level pressure anomaly of the 2001 October–December period (from the mean for 1971–2000). The stippled areas indicated areas more than 2 standard deviations away from the mean.

which did not significantly alter the positive ice anomalies present over the previous three months.

[9] During November, the largest negative low pressure anomaly at the latitude of the circumpolar trough shifted to the northern Bellingshausen Sea, resulting in strong north-westerly flow across the northern Weddell Sea and towards northern Dronning Maud Land. These conditions were responsible for the eastward spread of the negative ice anomalies to the eastern Weddell Sea, as shown in Figure 1b.

[10] During December, the negative pressure anomaly moved westwards to just west of the tip of the Peninsula, while the anticyclonic anomaly transferred westwards, creating an even stronger southwest to northeast surface pressure gradient across the northern Weddell Sea. This strong north-westerly flow created the negative ice anomalies along the full length of the northern Weddell Sea.

[11] Signals of the anomalous conditions were also apparent in the surface temperature observations from the research stations around the Weddell Sea. Esperanza station (63.4°S, 57.0°W), close to the tip of the Antarctic Peninsula, recorded mean temperatures of −0.5°C, 0.1°C and 2.0°C for October to December 2001. These values were respectively the second, third and second warmest monthly mean temperatures for the months in question in a record extending back to 1945. Because of the local orography, winds at Esperanza are not representative of the broad scale synoptic flow. On the other hand, at the nearby Marambio station they recorded increased north-westerly winds over the October to December period, confirming the extent to which warm, mid-latitude air masses were being advected into the north-west Weddell Sea.

[12] At Halley station the prevailing winds are from the east, with warmer episodes being associated with winds from a north-west to north-easterly direction. However, over the October to December 2001 period the winds at Halley were very similar to the long-term mean, with only a few more days of north-easterlies than normal. The temperatures were therefore close to the climatological mean.

[13] With no anomalously northerly flow along the coast of Dronning Maud land the question arises as to why there was such extensive ice compared to other years? Figure 4 shows the long term (1971–2000) mean December winds from the NNR and the mean winds for December 2001. These show clearly that in December 2001 warm north-westerly flow over the northern Weddell Sea would have melted the sea ice in the northern part of the area creating the negative sea ice anomalies. Figure 4 also shows that ice would have been advected towards Halley from the north and then down the coast of Dronning Maud land. The area of the western and south-western Weddell Sea normally has fairly high ice concentrations (Figure 2) but during late 2001 the lack of northward advection of ice to the east of the Peninsula resulted in convergence of sea ice along the edge of the Ronne Ice Shelf. This gave exceptionally high ice concentrations across the southwest Weddell Sea, so that despite strong northeasterly winds along the coast of Dronning Maud Land there was little ice advection, resulting in slow-moving, heavy ice conditions close to Halley.

4. Antarctic-Wide Anomalies

[14] The broad scale MSLP anomaly pattern shown in Figure 3 indicates that for October–December 2001 there was below average pressure around much of the Antarctic continent and above average pressure to the north. The Antarctic and Southern Ocean circulation over the period considered here was characterised by an amplified wave number 3 pattern, with the enhanced trough/ridge system over the Bellingshausen Sea/South Atlantic described above being the most pronounced feature. There were three marked positive anomaly centres north of the circumpolar trough, with the strongest located north of South Georgia at

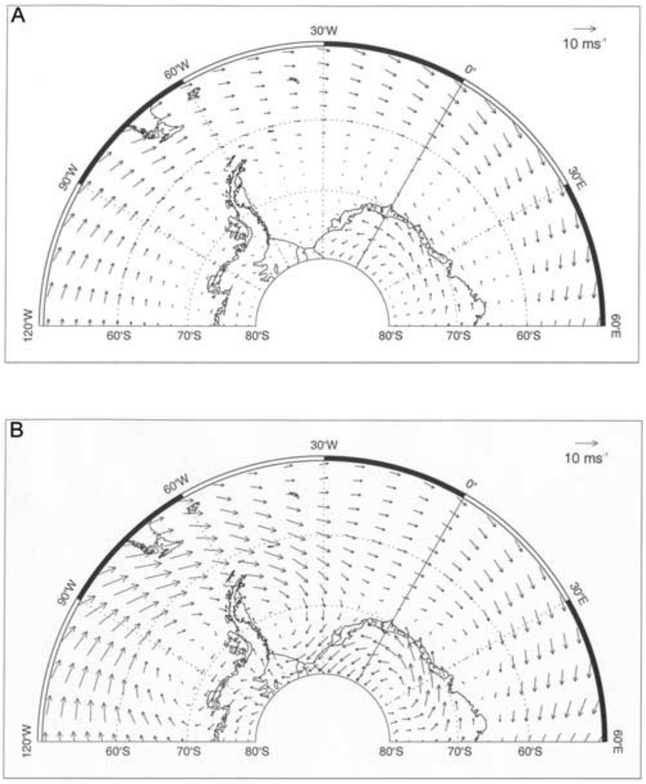

Figure 4. December winds from the NCEP-NCAR reanalysis (a) the 1971–2000 mean and (b) 2001.

50°S, 35°W, but further large, surface high MSLP anomalies near 150°W (southeast of New Zealand) and at 110°E (southwest of Australia). Although the negative anomaly centres also formed an approximate wave number 3 pattern, only the centre located in the Bellingshausen-Weddell Sea region exceeded two standard deviations. A small area of highly anomalous low MSLP was also present in the Ross Ice Shelf region, just south of the area of large seasonal and interannual variability of sea ice over the Ross Sea.

[15] In the Southern Hemisphere, anomaly patterns involving high MSLP blocking situations tend to be more short-lived than counterparts in the Northern Hemisphere [*Jones and Simmonds*, 1994], yet the conditions over this period proved remarkably persistent and resulted in anomalous conditions at a number of sites across the continent. At Dome C in East Antarctica (74.50°S, 123.00°E, elevation 3280 m) the European Programme for Ice Coring in Antarctic (EPICA) was undertaking a season of drilling and experienced a number of periods of slight to moderate snowfall (E. Wolff, personal communication) more typical of a coastal site than an interior location that usually only receives clear sky precipitation. This resulted from the persistent high pressure to the south and southwest of Australia bringing maritime air masses into the interior of the continent on its western flank (c.f. Figure 3).

[16] Vostok Station (78.5°S, 106.9°E, elevation 3488 m), on the plateau of East Antarctica, also experienced anomalously warm temperatures over this period, with the mean surface temperatures for November 2001 to January 2002 being respectively 2.2, 1.4 and 3.2°C warmer than the long term means, the latter figure being 1.5 sd above average. In addition, on 11 January 2002 the station experienced a temperature of −16.5°C, which was within 3°C of the absolute maximum temperature ever recorded at the station. During December, the wave number 3 pattern at 500 hPa was particularly enhanced and one of the low pressure centres was located over the Antarctic coast near 50°E. This resulted in strong northerly flow onto the continent around 90°E and towards Vostok, bringing warm, maritime air onto the high plateau.

5. Discussion

[17] The atmospheric circulation across high southern latitudes was clearly exceptional during the early part of the Austral summer of 2001/02 and the magnitude of some of the 2001 anomalies indicate they were unprecedented in the 1971–2000 re-analysis period. This was checked by ranking the NNR data at each grid point, which indicated that regions of unprecedented MSLP anomalies corresponded closely to normalised anomalies exceeding two standard deviations from the mean. It can be seen from Figure 3 that three anticyclonic and two cyclonic areas exceeded this 2 sd limit. In addition, the surface meteorological data from South Georgia (Halley) suggested that the high (low) pressure was the most anomalous within the approximately 100 (40) year record.

[18] The amplified wave number 3 pattern and the consequent increase in meridional flow had an impact on conditions across many parts of the continent. The strength and persistence of the northwesterly flow across the Weddell Sea was felt particularly strongly because of the impact on the sea ice and the effect on marine operations, coming as it did during the period when ice normally retreats rapidly along the coast of Dronning Maud Land. The particular configuration of MSLP anomalies of high pressure over the South Atlantic and low pressure over the southwest Weddell Sea/Antarctic Peninsula/Bellingshausen Sea was just about the ideal scenario for giving strong northwesterly flow to the east of the Antarctic Peninsula and building up sea ice over the southern Weddell Sea. Fortunately, atmospheric anomalies of this kind that persist for several months are very rare, as confirmed by the experiences of operating in this area, which suggest that the ice conditions were the worst for at least 50 years.

[19] The ultimate cause of the amplified wave number 3 pattern during late 2001 remains unclear. It is known that the El-Niño Southern Oscillation (ENSO) exerts an influence on atmospheric conditions in the Antarctic coastal region and particularly around the Peninsula [*Harangozo*, 2000]. Yet during the period of interest, tropical SST anomalies associated with ENSO were quite small and no similar, large atmospheric anomalies have occurred during previous major ENSO events. At present, it appears as though these very anomalous atmospheric conditions may have occurred as part of the natural variability of the high latitude circulation, but further work is taking place to examine the event as part of an investigation into the modes of variability of the Antarctic climate system.

[20] Although the anomalous atmospheric circulation over the Weddell Sea had a major impact on the sea ice, there were also possibly other consequences. During February 2002 there was a major breakout of 2,500 km^2 of ice from the Larsen-B Ice Shelf on the eastern side of the Peninsula just south of Esperanza. This area has experienced a series of breakouts in recent years [*Vaughan and Doake*, 1996] as temperatures have risen steadily since the 1950s. While it is clearly not possible to unequivocally link the disintegration of a particular part of an ice shelf with anomalously warm temperatures over a few months, it is not unreasonable to imagine that the anomalously high temperatures (and lack of sea ice to suppress swell) over this period played some role in the final collapse of the Larsen-B Ice Shelf.

References

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, NASA, Washington, D. C., 1992.
Harangozo, S. A., A search for ENSO teleconnections in the west Antarctic Peninsula climate in Austral winter, *Int. J. Climatol.*, *20*, 663–679, 2000.
Hines, K. M., D. H. Bromwich, and G. J. Marshall, Artificial surface pressure trends in the NCEP/NCAR reanalysis over the Southern Ocean and Antarctica, *J. Clim.*, *12*, 3940–3952, 2000.
Jones, D. A., and I. Simmonds, A climatology of Southern Hemisphere anticyclones, *Clim. Dyn.*, *10*, 333–348, 1994.
King, J. C., and J. Turner, Antarctic Meteorology and Climatology, 1-409, Cambridge University Press, Cambridge, 1997.
Marshall, G. J., and S. A. Harangozo, An appraisal of NCEP/NCAR reanalysis MSLP viability for climate studies in the South Pacific, *Geophys. Res. Lett.*, *27*, 3057–3060, 2000.
Parkinson, C. L., Interannual variability of monthly southern ocean sea ice distributions, *J. Geophys. Res.*, *97*(C4), 5349–5363, 1992.
Vaughan, D. G., and C. S. Doake, Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula, *Nature*, *379*, 328–331, 1996.
Yuan, X. J., and D. G. Martinson, The Antarctic Dipole and its predictability, *Geophys. Res. Lett.*, *28*, 3609–3612, 2001.

J. Turner, S. A. Harangozo, G. J. Marshall, J. C. King, and S. R. Colwell, British Antarctic Survey, National Environment Research Council, Cambridge, UK.