INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **33**: 852–861 (2013)
Published online 30 March 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3474

The impact of changes in sea ice advance on the large winter warming on the western Antarctic Peninsula

John Turner,* Ted Maksym, Tony Phillips, Gareth J. Marshall and Michael P. Meredith
British Antarctic Survey, Cambridge, UK

ABSTRACT: Over 1979–2007 near-surface air temperatures on the maritime western side of the Antarctic Peninsula have increased throughout the year, with the greatest monthly temperature rise of 1.7 °C dec^{-1} occurring in July as recorded at Faraday/Vernadsky (F/V) station (65.4 °S, 64.4 °W). The warming trend in this month has been the result of a loss of very cold days at the station with the average number of days with mean temperature below −15 °C decreasing from 7 during 1979–1988 to 0.6 over 1998–2007. There is a high anti-correlation between temperatures at F/V and the extent of sea ice in July just to the west of the station. Passive microwave satellite imagery reveals that monthly ice concentrations here have decreased by up to 25% since the late 1970s creating a polynya-like feature along the west coast of the peninsula. Sea ice extent over the southern Bellingshausen Sea has decreased markedly during the late summer and early autumn so that there has been a lengthening of the ice-free season. Yet faster ice advance in June as a result of changes in the meridional component of the wind means that the overall ice extent in the Bellingshausen Sea in July (offshore of the F/V region) has not changed significantly. Years of extensive sea ice can occur as frequently now as in the earlier part of the record, but a combination of the changing nature of the ice advance and subtle shifts in the wind direction have led to the more frequent occurrence of the ice-free area to the west of F/V in recent years. There are also indications of pre-conditioning of the ice/ocean system to the west of F/V well before winter that is associated with the presence or absence of the ice anomaly that is observed in July. Copyright © 2012 Royal Meteorological Society

KEY WORDS sea ice; Antarctic warming; Faraday station; Vernadsky station

Received 8 November 2011; Accepted 28 February 2012

1. Introduction

The western side of the Antarctic Peninsula has experienced remarkable environmental changes in recent decades, including a near-surface atmospheric temperature increase as large as any in the Southern Hemisphere (King *et al.*, 2003), the disintegration of floating ice shelves (Vaughan, 1993), an increase in the number of precipitation events (Turner *et al.*, 1997), the retreat of glaciers (Cook *et al.*, 2005), a 'greening' that has involved the expansion in range and local population numbers of various flora (Convey, 2003) and strong upper layer warming and salinification in the ocean (Meredith and King, 2005).

The largest recorded warming has been at Faraday (now Vernadsky) Station (65.4 °S, 64.4 °W) (subsequently F/V), from which meteorological records started in the late 1940s. These show a warming throughout the year (Vaughan *et al.*, 2001), but with greatest increase of temperature during winter (King, 1994; King *et al.*, 2003; Turner *et al.*, 2005). Radiosonde data from F/V indicate that the largest warming has been confined to the lowest layers of the atmosphere, with the temperature trends in the mid- to upper-troposphere being similar to those for the Southern Hemisphere as a whole (Marshall, 2002).

Monthly mean, satellite-derived surface skin temperatures across the Antarctic and Southern Ocean show that the F/V data correlate strongly with temperatures over the ocean just west of the Peninsula, moderately with temperatures east of the Peninsula, and poorly over the rest of the continent (King and Comiso, 2003).

A major factor influencing the F/V temperatures is cyclonic activity over the Amundsen-Bellingshausen Sea (ABS) through the depth and location of the Amundsen Sea Low (ASL). Warm (cold) winters on the western side of the Peninsula are associated with negative (positive) mean sea level pressure (MSLP) and upper-air height anomalies over the ABS, and anomalies of the opposite sign over the Weddell Sea (Marshall and King, 1998). During winters, when the ASL is deep (weak) and/or located further to the east (west), the climatological north to northwesterly wind down the western side of the Peninsula is stronger (weaker), and there is more (less) warm air advection. King (1994) noted the strong anti-correlation between winter season temperatures at F/V and the extent of sea ice to the west of the Peninsula. Here the sea ice passes north/south along the coast during the annual cycle of its expansion and retreat. As the presence of sea ice has a very strong influence on the flux of heat

* Correspondence to: J. Turner, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. E-mail: jtu@bas.ac.uk

between the ocean and atmosphere, winters of extensive (little) sea ice are associated with locally cold (warm) winters.

Since the late 1970s there has been a small overall positive trend in total Southern Ocean annual mean sea ice extent, but marked regional differences and particularly a negative (positive) trend in the ABS (Ross Sea) (Cavalieri and Parkinson, 2008; Comiso and Nishio, 2008; Turner *et al.*, 2009). Lefebvre *et al.* (2004) suggested that sea ice variability in the ABS was associated with changes in the Southern Annular Mode (SAM), which increased the meridional flow and gave greater advection of warm air.

There has also been a shortening of the sea ice season with later advance and earlier ice retreat over the ABS (Stammerjohn *et al.*, 2008a). These authors linked the observed changes, especially the sea ice advance, to decadal changes in the SAM and the high-latitude response to the El Niño–Southern Oscillation (ENSO). They found a greater high-latitude response to ENSO when a negative (positive) SAM coincided with El Niño (La Nina).

Before 1979, there were no broad scale sea ice analyses and the atmospheric re-analysis fields are not reliable across the Southern Ocean as there were no atmospheric sounding instruments flown on the polar orbiting satellites. However, since 1979, high quality six-hourly surface and upper-air meteorological analyses have been available from re-analysis projects, as well as daily fields of sea ice concentrations from satellite-borne passive microwave instruments. Here we use post-1979 daily mean *in situ* observations and daily/monthly mean atmospheric circulation and sea ice data to elucidate the causes of the marked winter season warming on the western side of the Antarctic Peninsula. We focus particularly on the decrease in the number of very cold days at F/V and the decrease in ice concentration immediately to the west of the station.

2. Data

In situ synoptic meteorological observations from F/V collected as part of the SCAR READER project (Turner *et al.*, 2004) are used here. These were thoroughly quality controlled and are complete over the period of interest. Surface and upper atmosphere circulation fields are used from the ECMWF re-analysis (ERA) project up to 2001, with operational ECMWF analyses used thereafter. Both the ERA six-hourly fields and the F/V six-hourly observations were averaged to create daily means. Mean daily and monthly sea ice concentration fields were obtained from the US National Snow and Ice Data Center, with the GSFC Bootstrap 2 algorithm (Comiso and Nishio, 2008) used to convert 1979–2007 SSM/I brightness temperatures into ice concentrations. The sea ice edge at particular longitudes was taken as the 15% ice concentration.

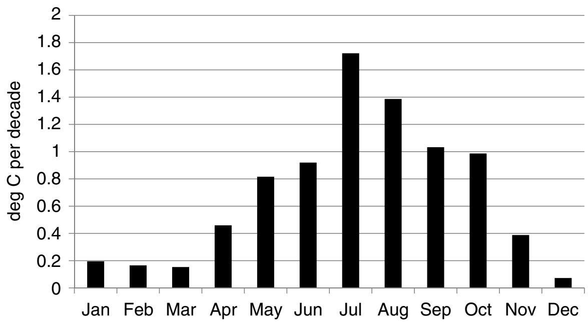

Figure 1. The annual cycle of near-surface air temperature trends at F/V for 1979–2007 (° C dec^{-1}).

3. Trends in the F/V *in situ* observations and sea ice concentrations over the Bellingshausen Sea

During 1979–2007, the F/V monthly mean surface temperatures increased throughout the year, with the smallest (greatest) temperature increases in summer (winter). The temperature trend (interannual standard deviation) rises rapidly from 0.15° dec^{-1} (0.94°) in March to a maximum of 1.72° dec^{-1} (3.89°) in July and then decreases at a similar rate into the spring (Figure 1).

Analysis of the daily mean July temperatures shows that there has been a decrease in the number of cold temperatures since 1979. On average, there were 7 d per July with daily mean temperature below −15 °C during 1979–1988, decreasing to 0.6 d per July during 1998–2007. There has been a corresponding increase in the number of days with temperatures between −15 °C and 0 °C, but little change in the number of days with temperatures above 0 °C. If the years with three or more cold days are excluded then the July temperature shows no significant trend, suggesting that it is the reduction in the number of cold days that is responsible for the trend. A further consequence of the loss of cold days has been that the standard deviation of the July temperatures has decreased at a statistically significant rate over the period 1979–2007.

The correlation of mean July station temperatures with July sea ice concentration across the Southern Ocean (Figure 2) shows that cold (warm) July temperatures at F/V are associated with extensive (reduced) sea ice around the Antarctic Peninsula (coast of East Antarctica), particularly off F/V. This pattern of contrasting change over the Antarctic Peninsula and elsewhere is the characteristic signal of several modes of Antarctic climate variability, including the SAM (Thompson and Solomon, 2002), the Pacific South American pattern and the Semi-Annual Oscillation (Yuan and Li, 2008). These modes all influence the depth and location of the ASL.

A decrease in ice concentration in excess of 20% has occurred in January along the southern Bellingshausen Sea, with losses of up to 15% down the west coast of the Peninsula (Figure 3(a)). There is also a reduction in sea ice concentration from February to May, although the greatest magnitude of the decrease drops from over 30% in February to about 15% in May. However, a

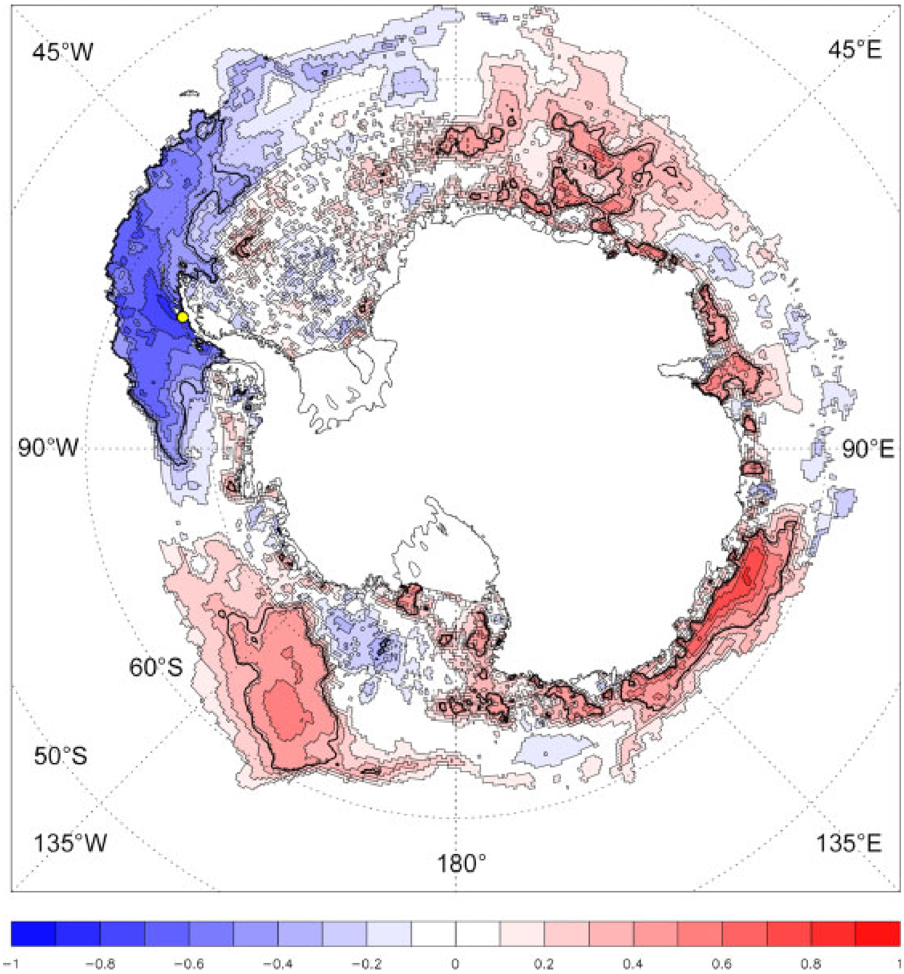

Figure 2. The correlation of F/V July mean surface temperatures with July mean sea ice concentrations for 1979–2007. The yellow circle marks the location of F/V (65.4 °S, 64.4 °W). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

major change in the spatial pattern of ice loss has occurred over the subsequent 2 months. In June, there has been virtually no decrease in ice concentration along the southern Bellingshausen Sea, but a decrease of about 20% close to the west coast of the Peninsula over 66–67 °S. In July (Figure 3(g)), the largest change (up to 25%) in ice concentration has been just to the west of F/V, with smaller losses further north. It is this loss of ice immediately to the west of F/V that has been responsible for the July warming at the station in recent decades.

The sea ice edge at 70 °W provides a valuable means of examining the seasonal evolution of sea ice extent and its decadal changes. This longitude is a few degrees to the west of F/V but the meridional record of sea ice evolution here extends northwards from Alexander Island to the sea ice edge. Over 1979–2007, the minimum ice extent occurred in March, with increases northwards of 28 and 184 km, respectively, in April and May (Figure 4). However, the largest monthly advance (253 km) takes place in June, with the ice edge reaching ~64 °S. Between May and June the ice edge also advances from the east around the tip of the Peninsula and southwards along the northwestern coast. The result is that by June there is, on average, an ice-free region along 62–65 °W between sea ice forming in the Bellingshausen Sea and ice originating near the tip of the Peninsula. In July, the ice advances another 100 km northwards along 70 °W and there has been further westward spread of sea ice from the tip of the Peninsula. However, there is still a zone of lower ice concentrations along 63 °W. It is the varying development of ice here that primarily controls July temperatures at F/V.

We will now examine trends in the sea ice advance since 1979. During the period from the ice minimum in March until the end of May the advance of ice along 70 °W has slowed (Figure 4), with the greatest decrease being during May when the advance has slowed by -50 km month^{-1} dec^{-1}. However, during June there has been a more rapid advance of 65 km month^{-1} dec^{-1}, such that there has been no significant trend in the July ice extent at this longitude. It should be noted that only the trends in June and December are significant at better than the 10% level.

This change in ice advance is consistent with trends in atmospheric circulation. The monthly trends in MSLP for 1979–2007 indicate a tendency towards lower MSLP over the ABS (Figure 5) from February to May, except March, when there has been a very slight tendency

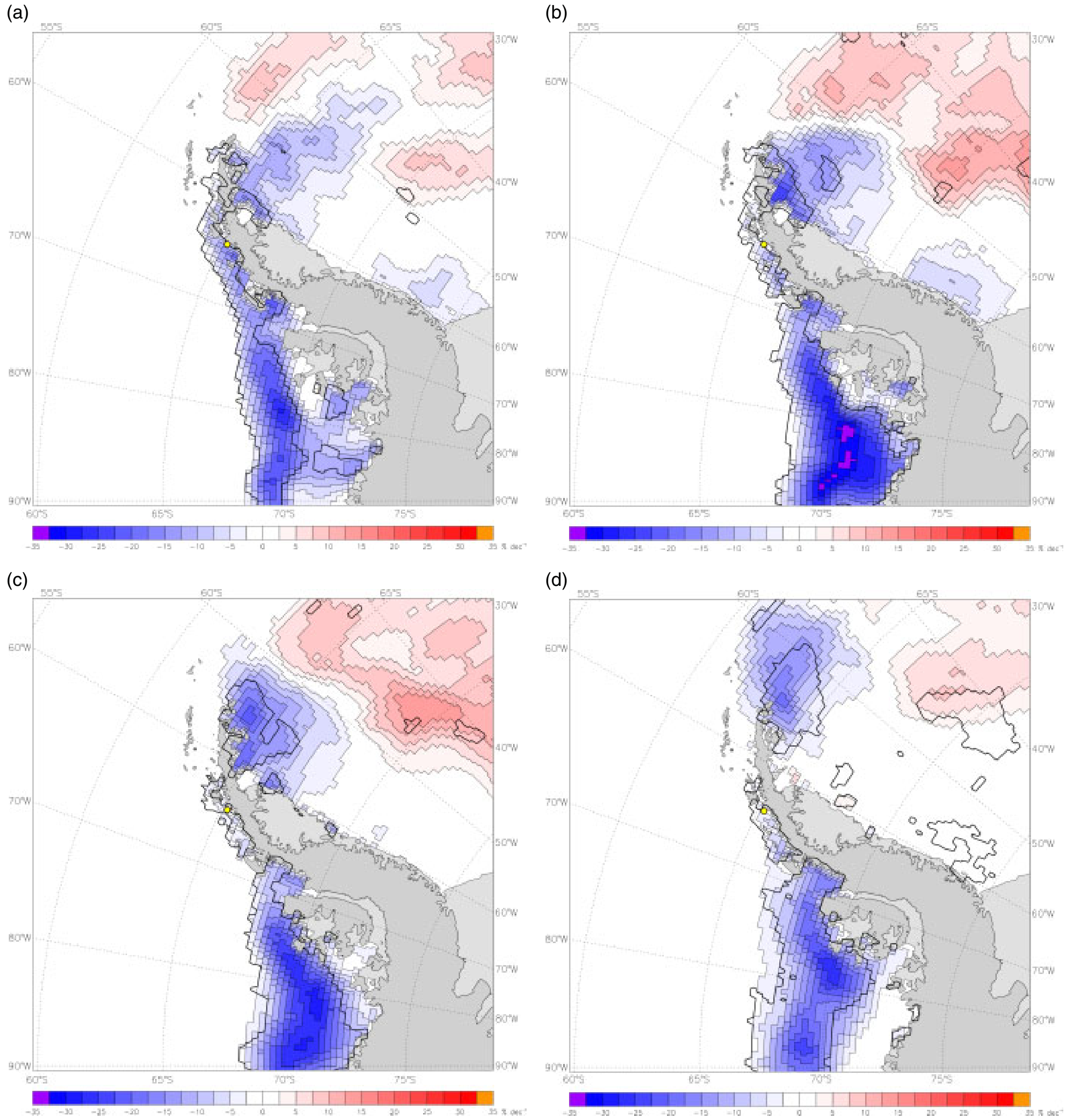

Figure 3. The trends in sea ice concentration for 1979–2007 (% dec^{-1}). (a) January, (b) February, (c) March, (d) April, (e) May, (f) June and (g) July. The location of Faraday/Vernadsky is shown by the yellow dot. The bold contours indicate areas where the trends are statistically significant at the 5% level. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

towards more anticyclonic circulation. The largest trend toward lower MSLP and therefore greater northerly flow onto the advancing sea ice in the Bellingshausen Sea has been in May (Figure 5(a)). This is consistent with the deceleration of sea ice advance, which has occurred between March and May (Stammerjohn *et al*., 2008a).

In both June and July, the tendency has been towards a more anticyclonic circulation over the ABS (Figure 5(b) shows the data for June). This has promoted greater southerly flow and the rapid advance of the ice edge noted above.

4. The development of the ice-free area off F/V

Although the timing of the ice advance has changed, there has been no significant trend in July ice extent over the Bellingshausen Sea as a whole, so that years of extensive ice are as likely to occur now as in the past (Harangozo, 2006). However, as Figure 3(g) shows, there is a regional trend towards less ice cover off the coast of F/V. This raises the question as to why the nature of the ice cover has changed, and is it related to the timing of the advance?

If there is very little sea ice across the Bellingshausen Sea (such as during the winters of 1988–1990, 1996, 1998–2000) then the temperatures at F/V are always going to be relatively warm. However, ice concentrations for each winter and the time series of F/V temperatures suggest that years of extensive ice can be divided into warm and cold years at F/V (see the caption to Figure 6 and Table I for a list of the years in each category). The separation of extensive ice years into warm or cold

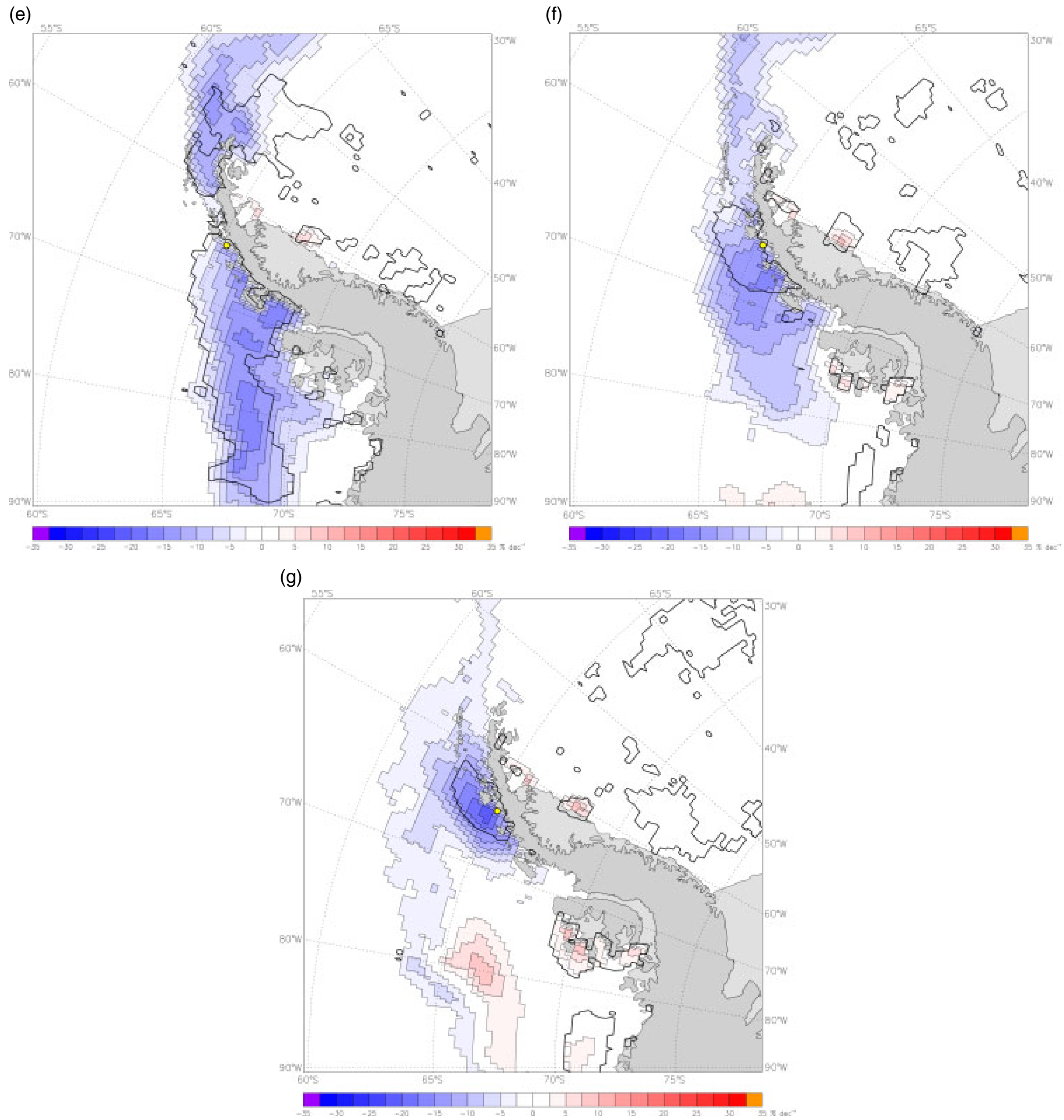

Figure 3. (*Continued*).

was based on the number of July days with temperatures below −15 °C. The twelve most extensive ice years were selected based on mean July ice extent along 70 °W. Cold years had six or more cold days, while warm years had three or fewer. Two years (1979 and 1981) were also included as cold years due to extensive ice along the coast, despite having less extensive ice along 70 °W. Exclusion of these years lessens the contrast between the two groups, but does not qualitatively alter the results. All other years with less extensive ice averaged less than one cold day. Figure 6 shows the mean ice anomalies from April to July for these two groupings of years (7 years in each group).

In cold years, ice was more extensive than normal in May, particularly close to the coast. This positive ice anomaly moved northwards along the coast during June, resulting in a strong positive ice anomaly off F/V in July consistent with Figure 3. During warm years there was a positive ice anomaly in April only to the west of Adelaide Island, but its magnitude was much smaller. However, stronger southerly winds (as indicated by the MSLP anomaly contours; corresponding monthly mean MSLP fields for the two groups are shown in Figure 7) in June and July led to a more rapid ice advance in warm years, particularly in the central and western Bellingshausen Sea. This is consistent with the overall trends in MSLP, ice advance and temperatures described above as most of the cold, extensive ice years occurred earlier in the 29-year period, while most warm, extensive ice years occurred in the latter half of the period. During

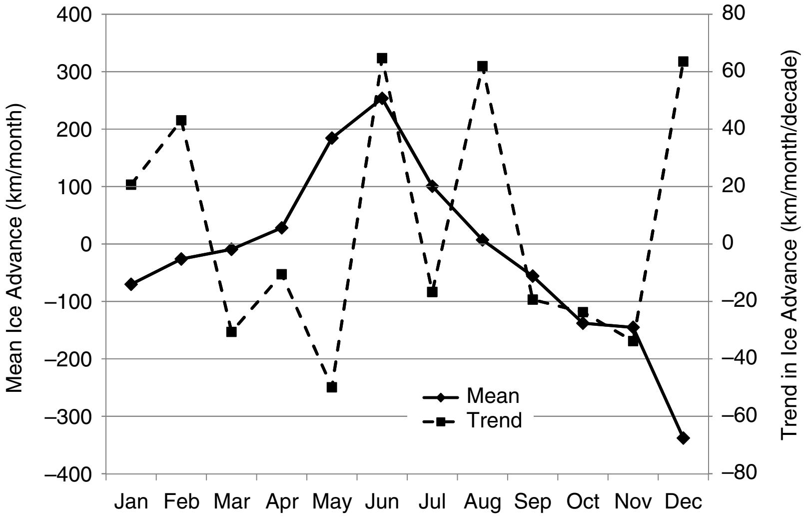

Figure 4. The mean annual cycle of sea ice advance/retreat along 70 °W (solid line, km month^{-1}) and trend (km month^{-1} dec^{-1}) over 1979–2007 (broken line). Ice advance is computed between the first and last day of each month.

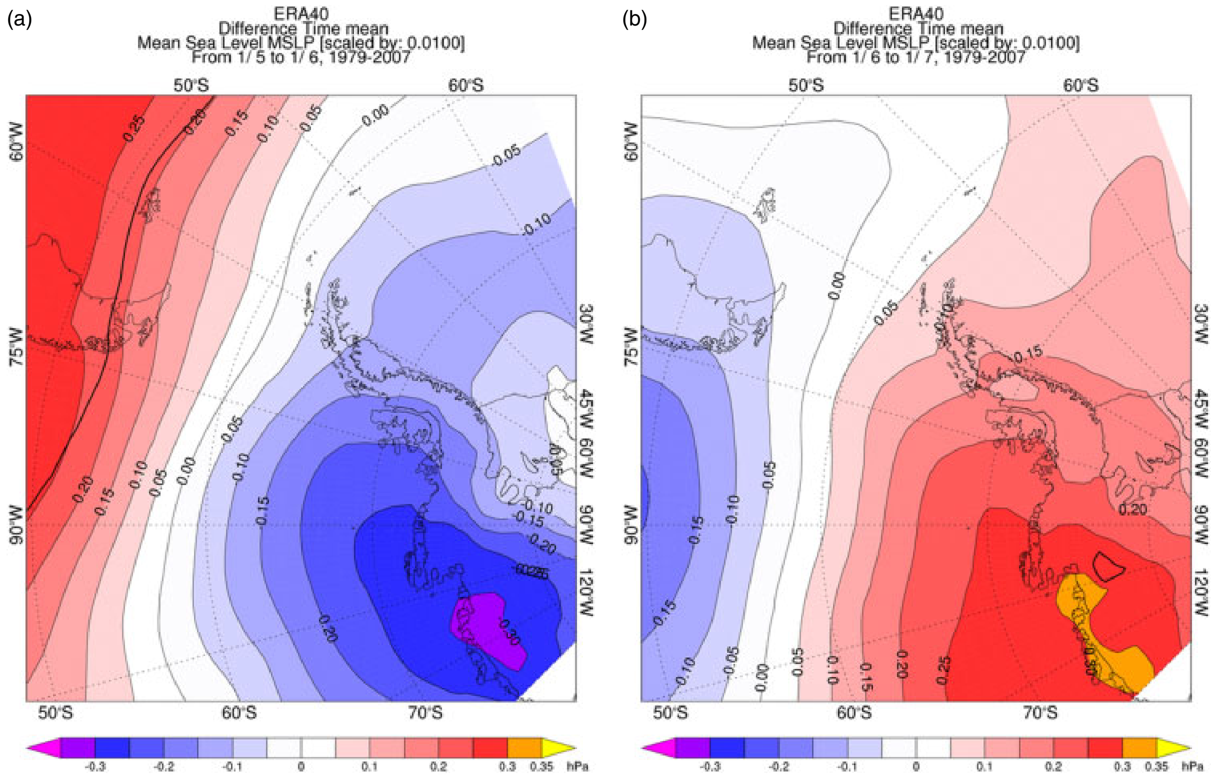

Figure 5. MSLP trends (hPa year^{-1}) for 1979–2007. (a) May and (b) June. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

warm years there is more extensive ice in the central and western Bellingshausen Sea than in cold years, whereas there is more ice in the northeastern Bellingshausen Sea in cold years. From the MSLP anomaly fields, it can be seen that from May to July the warmer years have a stronger southerly component as a result of higher MSLP over the Bellingshausen Sea. The shape of the Peninsula may also play a role, in that more southerly winds in June would tend to push ice away from the coast as it curves eastward north of Adelaide Island.

The cold years have very small circulation anomalies in April and even a small eastern anomaly in May, although the actual circulation (Figure 7) still has west to northwesterly flow to pin the sea ice to the coast. The MSLP anomalies in June are small, but by July would encourage a stronger southerly flow.

In the 15 years with less extensive sea ice the greatest ice advance was delayed by about a month compared to the warm and cold extensive ice years, with the maximum advance taking place in June rather than May. In the

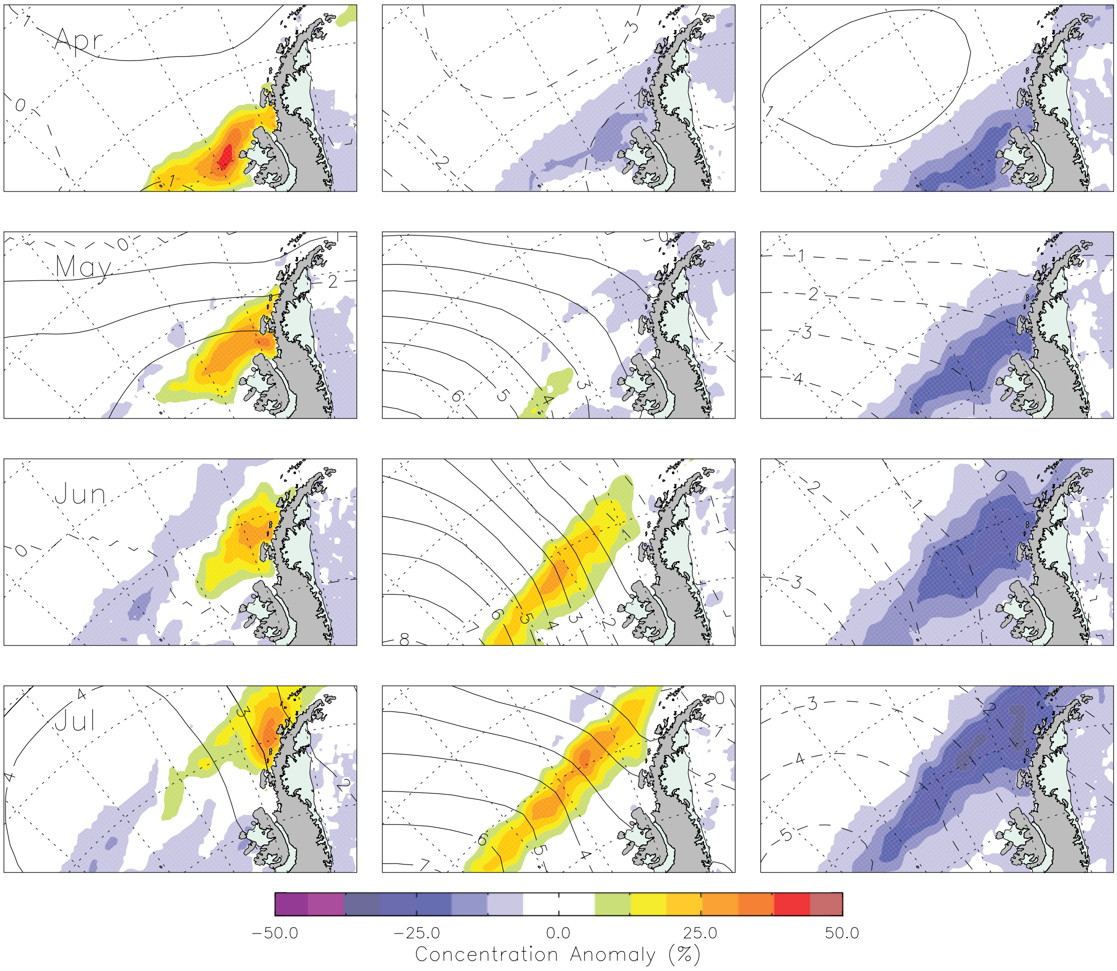

Figure 6. Mean sea ice anomalies (colours) and monthly mean MSLP anomaly (contours) for extensive ice years over 1979–2007 when temperatures at F/V were cold (left), warm (centre) and years of little ice (right) in July. See Table I for a list of years in each category. Data for April to July are shown from top to bottom. Latitude/longitude values are omitted for clarify, but the parallels and meridians range from 55–70 °S to 40–110 °W. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table I. July temperature and sea ice data for the three categories (1) extensive sea ice/cold F/V temperature, (2) extensive sea ice/warm F/V temperature and (3) less extensive sea ice. The division of the years into these three groups is described in the text.

Category	Extensive/cold		Extensive/warm		Less extensive sea ice	
Years	1979	1987	1986	2001	1983	1998
	1980	1992	1991	2002	1984	1999
	1981	1994	1995	2005	1985	2000
	1982		1997		1988	2003
					1989	2004
					1990	2006
					1993	2007
					1996	
Mean July sea ice extent at 70 °W (km)	745.2		767.2		546.1	
Mean F/V July air temperature (°C)	−12.6		−7.4		−4.6	
Mean number of July days at F/V with a temperature below −15 °C	12.1		1.3		0.7	

subsequent months, the amount of advance was very similar for all three categories of ice extent/temperature, but the slow start to the advance in the years with less ice resulted in an overall smaller amount of ice at 70 °W by the time of the ice maximum. These years resulted in relatively warm years at F/V and very few days with temperatures less than −15 °C (Table I).

The differences in atmospheric circulation anomalies between cold and warm years in Figure 6 are subtle. This can be appreciated from Figure 7 which shows that in

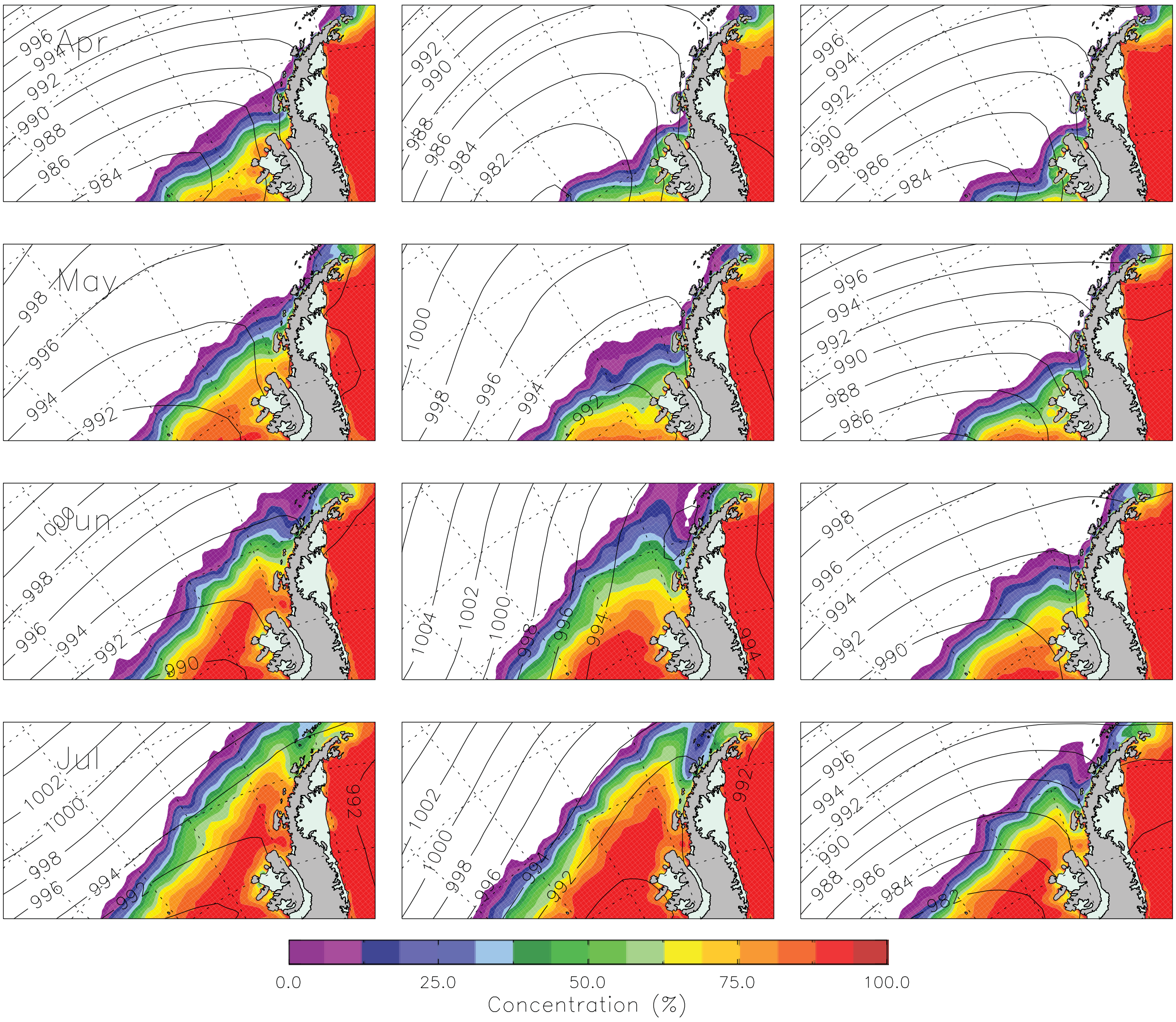

Figure 7. Mean sea ice concentrations (colours) and monthly mean MSLP (contours) for extensive ice years over 1979–2007 when temperatures at F/V were cold (left), warm (centre) and when there was little sea ice (right) in July. See Table I for a list of years in each category. Data for April to July are shown from top to bottom. Latitude/longitude values are omitted for clarify, but the parallels and meridians range from 55–70 °S to 40–110 °W. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

both warm and cold extensive ice years there is always low pressure to the west or southwest of Alexander Island and higher pressure over the northern Bellingshausen Sea. But slight variations in the location and depth of these features can have important consequences on the ice distribution. Surprisingly, in the warmer years there is generally weaker northerly flow across the whole Bellingshausen Sea from May to July. This is consistent with extensive ice in these years. The starting point for the ice advance in April is different between warm and cold years, with positive (negligible) ice anomalies over the southeast Bellingshausen Sea in cold (warm) years. This sea ice pattern suggests some pre-conditioning of the ice/ocean system well before winter that contributes to the presence or absence of the ice anomaly that is observed in July (Weatherly *et al.*, 1991).

The day of ice retreat in the previous spring is directly related to the length of the open water season prior to ice advance the following winter; this is a controlling factor in the amount of energy input into the upper ocean during summer (Stammerjohn *et al.*, 2008a). Thus an earlier retreat means more heat must be removed the following winter before ice can be formed and hence a predisposition for open water and warmer temperatures in July. This is supported by analysis of remotely sensed SSTs (not shown), and echoes the findings of previous work, which has shown that upper-ocean temperatures are increasing at the Peninsula, caused by increased heat flux from the atmosphere, and with the diminishing sea ice acting as a positive feedback to sustain and enhance both the oceanic and atmospheric warming (Meredith and King, 2005). This process will also add a tendency toward interannual persistence in the anomalies created.

With regard to the role of the length of the ice-free season in determining the trends in sea ice and atmospheric temperature, Figure 8 shows the mean difference in day of ice retreat in the previous spring between the cold and warm extensive ice year groups. Day of retreat is defined following Stammerjohn *et al.* (2008a) as the last day of the winter/spring that the ice concentration was above 50% (this avoids small areas of persistent ice along the coast affecting results). On average, years of

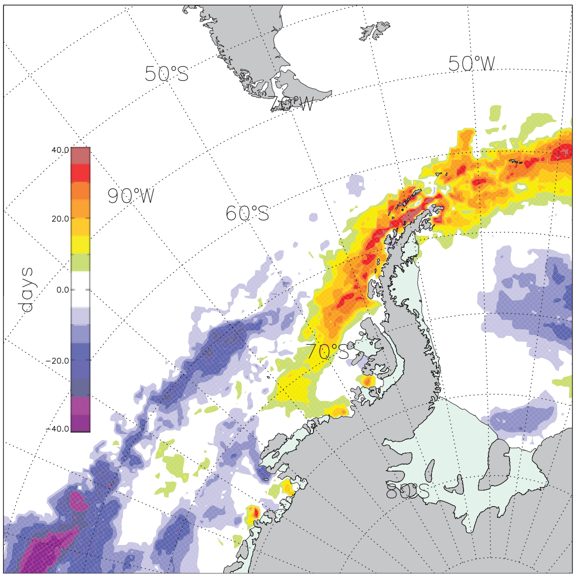

Figure 8. The difference in day of spring ice retreat between cold and warm extensive ice years the following July. The cold and warm extensive ice years were those listed in the caption to Figure 6. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

extensive ice with cold Julys had an ice retreat off the northwestern coast of the peninsula about a month later than warm, extensive ice years, while ice retreat was about 20 d earlier in the western Bellingshausen Sea (see also Stammerjohn *et al.*, 2008b). This pattern matches the June and July ice anomalies for each group in Figures 6 and 7, strongly suggesting a link between winter ice distribution and retreat the previous spring. Interestingly, the greatest difference in day of retreat between the two groups of years occurs precisely in the area of large ice loss just off F/V, suggesting that this region may be most sensitive to changes in ice seasonality.

In addition to the surface layers, it has been shown that the deep ocean at the Peninsula is warming, caused by enhanced wind-driven upwelling of deep waters from the Antarctic Circumpolar Current onto the shelf (Martinson *et al.*, 2008). This will affect the upper layers most significantly in regions where vertical mixing in the ocean is strongest, such as near the coastline where the interaction of wind-induced flows and internal tides with topography can lead to strong vertical displacements within the water column (Wallace *et al.*, 2008). Most importantly, coastal polynya-like conditions that persist during winter are known to create deep mixed layers, with the effect of mixing upward significantly greater quantities of heat from the warmer deep layers in the ocean, and hence contributing to the lengthening of the ice-free season (Meredith *et al.*, 2004). Further oceanic measurements would be needed at F/V to test the local quantitative importance of these processes, however, it seems likely that these will enhance further the role of the ocean in determining the trends in sea ice and atmospheric temperature.

5. Discussion and conclusions

The large warming trend at F/V has been the result of the development of a polynya-like feature just off the west coast of the Antarctic Peninsula during mid-winter. However, determining the precise mechanisms behind the ice loss is difficult because of the large natural variability in ice extent, driven partly by large-scale modes of climate variability, such as the SAM and ENSO. While these modes of variability drive much of the variability in ice extent here, they do not explain the trends since neither the SAM nor indices of ENSO show significant trends during the winter (Lefebvre *et al.*, 2004; Liu *et al.*, 2004).

As noted by Stammerjohn *et al.* (2008a), the La Nina state of ENSO and positive SAM were in phase during the 1990s, but out of phase during the 1980s, which led to the decreasing trends in sea ice season west of the Peninsula. Loss of stratospheric ozone has deepened the ASL over the last 30 years, particularly in May (Turner *et al.*, 2009), contributing to the increased northerly winds that have delayed ice advance.

While the marked trends in ice season clearly will impact air temperatures in the region (Steig *et al.*, 2009), our results show that mid-winter temperatures at F/V are not directly due to the trends in ice extent. Rather it is a change in the nature of the ice advance which is the proximate cause. Trends towards an earlier ice retreat in the west Antarctic Peninsula region are correlated with a delayed advance in the subsequent winter, coupled with a pre-conditioning of the ice-ocean system in the region (Stammerjohn *et al.*, 2008a). Upper-ocean processes are believed to be important, including storage of heat during the summer that must then be lost to the atmosphere during autumn before ice formation can commence, and possibly the creation of deeper mixed layers in winter that entrain more heat from below into the surface ocean layers. This has the greatest effect off F/V where a shift to earlier spring ice retreat has been greatest. An increased rate of ice advance in June due to more southerly winds has largely compensated for the decreased length of the ice-covered season. However, ocean pre-conditioning combined with subtle shifts in the wind direction and timing of the advance have kept the ice away from the coast and led to an increase in occurrence of the polynya-like feature. Determining the precise causes for the increased occurrence of the ice-free region are difficult because the changes in atmospheric forcing are subtle, there is a lack of long-term oceanographic data in this region, and the region of importance is small, presenting a challenge for our current modelling capabilities in the region. However, it is important to be able to simulate correctly these complex atmosphere–ocean–sea ice interactions in the Antarctic Peninsula region within climate models, so that we can have faith in the predictions for the next century. However, the coupled model simulations of change for the 20th century do not reproduce the magnitude of the observed warming on the western side of the

Peninsula and the polynya-like feature documented in this paper (King *et al.*, 2003). This is perhaps not surprising considering the relatively coarse horizontal resolution of the current generation of models, the difficulty of simulating the highly variable sea ice and the large variability in the ocean conditions in the models. Hopefully, limited area, high resolution coupled models may soon be able to handle such complex interactions more realistically so that climate predictions can be improved. In addition, such developments in modelling should give greater insight into the physical processes at work in this area of rapid climate change.

References

Cavalieri DJ, Parkinson CL. 2008. Antarctic sea ice variability and trends, 1979–2006. *Journal of Geophysical Research Oceans* **113**(C07004): DOI: 10.1029/2007JC004564.

Comiso JC, Nishio F. 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I and SMMR data. *Journal of Geophysical Research* **113**(C02S07): DOI: 10.1029/2007JC004257.

Convey P. 2003. Maritime Antarctic climate change: signals from terrestrial biology. In *Antarctic Peninsula Climate Variability: Historical and Palaeoenvironmental Perspectives*, vol 79 Domack E, Burnett A, Leventer A, Convey P, Kirby M, Bindschadler R (eds). *Antarctic Research Series*. American Geophysical Union: Washington DC, 145–158.

Cook AJ, Fox AJ, Vaughan DG, Ferrigno JG. 2005. Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* **308**: 541–544.

Harangozo SA. 2006. Atmospheric circulation impacts on winter maximum sea ice extent in the west Antarctic Peninsula region (1979–2001). *Geophysical Research Letters* **33**(L02502): DOI: 10.1029/2005GL024978.

King JC. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. *International Journal of Climatology* **14**: 357–369.

King JC, Comiso JC. 2003. The spatial coherence of interannual temperature variations in the Antarctic Peninsula. *Geophysical Research Letters* **30**(1040): DOI: 10.1029/2002GL015580.

King JC, Turner J, Marshall GJ, Connolley WM, Lachlan-Cope TA. 2003. Antarctic Peninsula climate variability and its causes as revealed by instrumental records. In *Antarctic Peninsula Climate Variability: Historical and Palaeoenvironmental Perspectives*, vol. 79, Domack E, Burnett A, Leventer A, Convey P, Kirby M, Bindschadler R (eds). *Antarctic Research Series*. American Geophysical Union: Washington DC, 17–30.

Lefebvre W, Goosse H, Timmermann R, Fichefet T. 2004. Influence of the Southern Annular Mode on the sea ice-ocean system. *Journal of Geophysical Research* **109**(C09005): DOI: 10.1029/2004JC002403.

Liu JP, Curry JA, Martinson DG. 2004. Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters* **31**(L02205): DOI: 10.1029/2003GL018732.

Marshall GJ. 2002. Trends in Antarctic geopotential height and temperature: a comparison between radiosonde and NCEP-NCAR reanalysis data. *Journal of Climate* **15**: 659–674.

Marshall GJ, King JC. 1998. Southern Hemisphere circulation anomalies associated with extreme Antarctic Peninsula winter temperatures. *Geophysical Research Letters* **25**: 2437–2440.

Martinson DG, Stammerjohn SE, Iannuzzi RA, Smith RC, Vernet M. 2008. Western Antarctic Peninsula physical oceanography and spatio-temporal variability. *Deep-Sea Research Part II-Topical Studies in Oceanography* **55**(18–19): 1964–1987.

Meredith MP, King JC. 2005. Climate change in the ocean to the west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters* **32**(L19606): DOI: 10.1029/2005GL024042.

Meredith MP, Renfrew IA, Clarke A, King JC, Brandon MA. 2004. Impact of the 1997/98 ENSO on upper ocean characteristics in Marguerite Bay, western Antarctic Peninsula. *Journal of Geophysical Research-Oceans* **109**(C9): DOI: 10.1029/2003JC001784.

Stammerjohn S, Martinson DG, Smith RC, Yuan X, Rind D. 2008a. Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño-Southern Oscillation and Southern Annular Mode variability. *Journal of Geophysical Research* **113**(C03S90): DOI: 10.1029/2007JC004269.

Stammerjohn SE, Martinson DG, Smith RC, Iannuzzi RA. 2008b. Sea ice in the western Antarctic Peninsula region: Spatio-temporal variability from ecological and climate change perspectives. *Deep-Sea Research Part II-Topical Studies in Oceanography* **55**(18–19): 2041–2058.

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC, Shindell DT. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature* **457**: 459–462.

Thompson DWJ, Solomon S. 2002. Interpretation of recent Southern Hemisphere climate change. *Science* **296**: 895–899.

Turner J, Colwell SR, Harangozo SA. 1997. Variability of precipitation over the coastal western Antarctic Peninsula from synoptic observations. *Journal of Geophysical Research* **102**: 13999–14007.

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Iagovkina S. 2004. The SCAR READER project: towards a high-quality database of mean Antarctic meteorological observations. *Journal of Climate* **17**: 2890–2898.

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Iagovkina S. 2005. Antarctic climate change during the last 50 years. *International Journal of Climatology* **25**: 279–294.

Turner J, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle TJ, Maksym T, Meredith MP, Wang Z, Orr A. 2009. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophysical Research Letters* **36**(L08502): DOI: 10.1029/2009GL037524.

Vaughan DG. 1993. Implications of the break-up of Wordie Ice Shelf, Antarctic for sea level. *Antarctic Science* **5**: 403–408.

Vaughan DG, Marshall GJ, Connolley WM, King JC, Mulvaney R. 2001. Climate change – devil in the detail. *Science* **293**: 1777–1779.

Wallace MI, Meredith MP, Brandon MA, Sherwin TJ, Dale A, Clarke A. 2008. On the characteristics of internal tides and coastal upwelling behaviour in Marguerite Bay, west Antarctic Peninsula. *Deep-Sea Research Part II-Topical Studies in Oceanography* **55**(18–19): 2023–2040.

Weatherly JW, Walsh JE, Zwally HJ. 1991. Antarctic sea ice variations and seasonal air temperature relationships. *Journal of Geophysical Research* **96**: 15119–15130.

Yuan XJ, Li CH. 2008. Climate modes in southern high latitudes and their impacts on Antarctic sea ice. *Journal of Geophysical Research-Oceans* **113**(C6): DOI: 10.1029/2006JC004067.

