P1.1 THE ROLE OF THE ATMOSPHERIC CIRCULATION IN VERY EXTENSIVE SUMMER SEA ICE IN THE ROSS SEA, ANTARCTICA IN 2003

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1. INTRODUCTION

Summer sea ice in both polar regions is undergoing dramatic changes with record areas of open water in the Arctic in the last few years (see www.nsidc.org) and also in the mildest Antarctic region of the Bellingshausen Sea (Stammerjohn et al., 1997) in the late 1980s and early 1990s. In sharp contrast to the Arctic, however, summer sea ice changes in other Antarctic regions differ and, in particular, summer open water in the Ross Sea (RS) (Fig. 1a) is decreasing with a record minimum extent of open water in February 2003 (Fig. 1b). Like the Arctic, there is evidence of a long-term warming in the Bellingshausen Sea but in the RS, in contrast, there is no evidence of any cooling having taken place here in recent decades.

This paper investigates the lack of open water in the RS in the 2003 austral summer (Fig. 1b) when it was just 25% of the long-term average (Arrigo and van Dijken, 2003, hereafter AVD03.) Fig. 1b shows that the southern RS near the Ross Ice Shelf (RIS) remained largely ice covered in summer even though open water is usually widespread here. Positive ice concentration anomalies first developed in October 2002 (Fig. 2a) and became much more extensive from November onwards. AVD03 proposed that a very large iceberg known as C-19 in the western RS (Fig. 1a) dammed large amounts of ice in the 2002 spring and following summer. The paper focuses on two explanations for this event: damming of ice by C-19 that usually drifted northwards and an anomalous atmospheric circulation that greatly reduced the divergent ice drift that normally occurs here (AVD03).

2. METHOD

This study uses ice extent, ice motion and atmospheric circulation data to study the evolution of the 2003 anomaly. Monthly average ice concentration (see polar.ncep.noaa.gov/seaice) and ice motion fields (Fowler, 2003) have been derived from Defense Meteorogical Satellite Programme passive microwave data.

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Seasonal averages and anomalies from the long-term mean (1979-2001) have also been calculated for the 2002 austral spring (October-December). This study uses monthly average 10 m *U* and *V* wind component fields from the reanalyses of the NOAA/National Center for Environmental Prediction (NCEP) for 1979-2003 (Kalnay et al., 1996). In a detailed study Harangozo and Connolley (2005), hereafter HC05, has shown that ice motion and winds are very strongly correlated in the southern RS.

3. RESULTS

This study has focussed on two features of the RS ice cover in the 2002 spring and one in the summer. The first spring feature is the disruption of the normal northward drift of ice. Any explanation for the lack of summer open water must taken into account why the spring 2002 ice cover persisted into summer. This is because summer air temperatures are generally too high for ice to form at this time. The impact of a highly anomalous atmospheric circulation in the 2002 spring is focussed on. Evidence is also sought for the freezing season being extended into the late spring. Lastly, the very early and rapid closure of open water in February 2003 (AVD03) is examined. The results are used to consider whether C-19 contributed significantly to the record minimum extent of summer open water.

3.1 *Disruption of divergent ice drift in the 2002 spring*

The Ross Sea ice cover, notably in the austral spring, is dominated by divergent northward ice motion in most years but Figs 2 and 3 show this failed to happen in spring 2002. In particular, in October an average southward, i.e. poleward, drift of ice occurred in the eastern and central RS that extended all the way to the RIS. November was also very anomalous with negligible ice drift throughout the RS. Strikingly, over the whole 2002 spring the greatest reduction in northward ice drift occurred in the eastern and central RS (Fig. 3), i.e. not in the vicinity of C-19 iceberg in the western RS.

Comparing Figures 3 and 4 shows that the area of greatest disruption of the normal northward ice drift along and north of the eastern half of the RIS in the 2002 spring also had the most anomalous winds. Here southerly winds were up to two standard deviations below-normal and this was mirrored in the ice motion. Clearly, therefore, an anomalous atmospheric circulation helped to ensure that the ice cover stayed intact into the warmest summer months. The significance of the anomalous ice drift is considered further below.

3.2. *Extended freezing season*

Another observation that needs to be explained is why the western part of the RS remained largely ice covered into the 2003 summer even though C-19 moved rapidly north here until the end of November (AVD03). Ice drift into this area from further east appears to have been small during the 2002 spring (Fig. 2) but the average surface air temperature at the U.S. McMurdo station (Fig. 1a) for this period was –10.4^{o} C. This was the lowest since 1988. In particular, monthly average temperatures of -16.7^{o} C in October 2002 and -10^{o} C in November were low enough for ice to continue forming into the late spring.

3.3 *Closure of open water in February 2003*

Routine observations from a cruise of the *Nathaniel B. Palmer* research ship in the RS in February 2003 indicate new ice was widespread in the central and western RS south of 73^{o} S after the 10th of February, i.e. the same time satellite data show open water areas starting to close (see AVD03: Fig. 2d). The ship reports, mainly made between 175^{o} E-170^{o} W, indicate 2-4 tenths of new or grey ice and thin first year ice of 30-60 cm were widespread from this time. By the 20th February 6-8 tenths ice cover was regularly reported and almost complete coverage occurred soon after. The *Palmer* reports also confirm sea surface temperatures (SSTs) were often around the freezing point (about -1.8^{o} C) after mid-February when ice formed around the ship.

In contrast to the 2002 spring, neither the atmospheric circulation or surface air temperatures were unusual in the western RS in February 2003. Cold ocean advection is also unlikely to account for the rapid closure of open water areas. If there had been much cold advection this would have supported more extensive ice than usual not only in summer but the preceding spring. This is because ocean heat anomalies only move slowly in regions like the RS where currents are mostly weak. In fact, there was less ice than normal over much of the northern RS in the 2002 spring (Figs 2a-c).

Based on all the available data, the most likely explanation for the early closure is that the extensive ice cover from the 2002 spring greatly reduced absorption of solar radiation in the ocean mixed layer during summer. Reports from the *Palmer* in early February 2003 confirm SSTs around 72.5-75^{o} S, ~175^{o} E were already at or near freezing around –1.4 to –1.8^{o} C at this time. Air temperatures were also dropping here in early February, generally being between –4 and –6^{o} C, thus ensuring SSTs stayed low. With SSTs close to the freezing point new ice formation could thus have been expected to begin as soon as air temperatures dropped to around –8^{o} C. In fact, they were frequently below –8^{o} C after mid-month when new ice began forming around the *Palmer.*

4. DISCUSSION AND CONCLUSIONS

This analysis and all the supporting observations indicate that the record minimum open water in the 2003 summer was primarily due to an anomalous atmospheric circulation in the 2002 spring along with unusually cold conditions in the western RS. In particular, the northerly winds in the central and eastern RS would have created an extensive 'plug' of compacted and compressed ice. Once formed such a plug would have been difficult to dislodge because of the large C-19 iceberg nearby.

Analysis of other years of extensive summer ice in the RS (HC05) and the Weddell Sea (Turner et al., 2003) indicates that these plugs of ice are quite common and become very persistent once formed with no large icebergs being present. At least part of the reason for this is that the lack of leads prevents summer warming of the mixed layer. This in turn helps to ensure that the ice stays intact. Independent observations of the sea ice cover in the Bellingshausen Sea during similar meteorological conditions to those in the RS in the 2002 spring indicates ice compaction during storms can be very considerable with ice thicknesses reaching up to 20m (Massom, pers comm).

However, the persistence of extensive ice into the summer had one further major effect. This was to keep SSTs in much of the coastal seas close to freezing, i.e. the extensive ice cover predisposed the ocean to early freezing in the late 2003 summer. There is other evidence (AVD03) that ice formation begins earlier in early autumn when the spring of the previous year is cold.

Finally, a comparison with another summer when the second lowest amount of open water occurred (HC05) in the RS in 1998 reveals close similarities in terms of the atmospheric circulation and its impact in disrupting the normally divergent sea ice drift. Unlike the 2003 summer no large icebergs occurred in the RS in this case. Air temperatures were mostly not unusual but the warmest November on record occurred in 1997. This emphasises that the freezing season was not prolonged in this year, i.e. the retention of the ice cover into the summer was entirely due to anomalous ice drift.

Based on this comparison and the analysis of 2002/03, it is concluded that an anomalous springtime atmospheric circulation was crucial in bringing about the record low amount of summer open water in the RS. It is further concluded that open water in the 2003 summer would have been very limited even if C-19 had not occurred.

References

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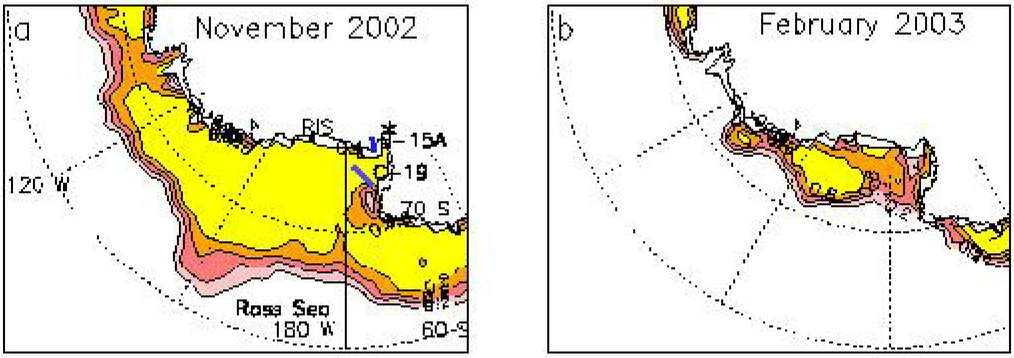

Figure 1. Ross Sea monthly average ice concentrations for (a) November 2002 and (b) February 2003 expressed as a fraction where 1 indicates complete ice cover, 0.5 is 50% ice cover. Positions of icebergs 'B-15' and 'C-19' in November 2002 are marked by short blue bars. McMurdo station is asterisked, RIS is the Ross Ice Shelf and the dateline is highlighted. B-15 was stationary and C-19 only moved slowly north after November 2002.

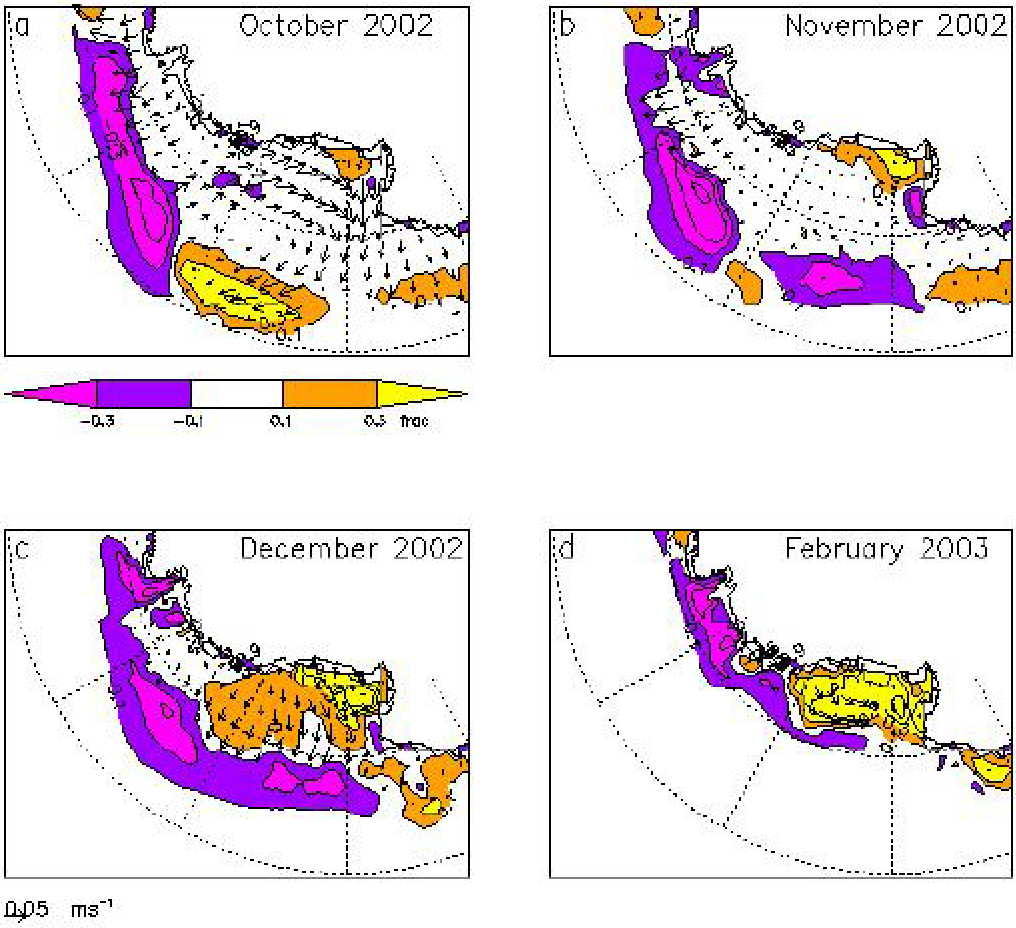

Figure 2. Ross Sea monthly average ice motion vectors (m/s) (arrows) and monthly ice concentration anomalies expressed as fractions for October-December 2002 (a-c) and February 2003 (d).

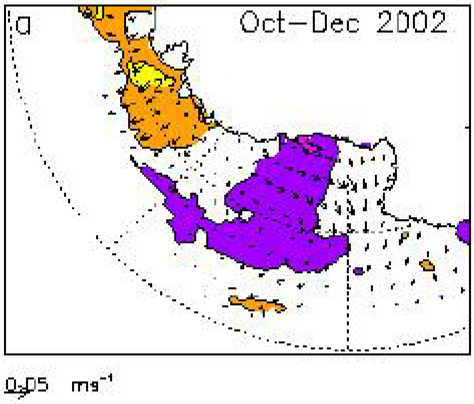

Figure 3. Spring (October-December) 2002 average ice motion (vectors) and standardized departures (shaded) of the seasonal average *V* component of ice motion from the 1979-2002 mean. Areas shaded blue and cerise indicate below-normal northward ice drift.

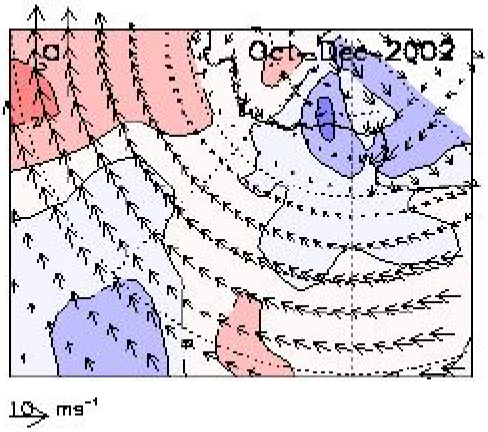

Figure 4. Spring 2002 average 10 m wind (vectors) and standardized departures of the seasonal average *V* component of 10 m wind (shaded) from the 1979-2002 mean. Areas shaded blue indicate below-normal southerly winds.