The Role of the Atmospheric Circulation in the Record Minimum Extent of Open Water in the Ross Sea in the 2003 Austral Summer

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ABSTRACT *The contribution of the atmospheric circulation to a record minimum extent of open water in the polar Ross Sea (RS) region in the 2003 austral summer is examined. Two major findings are reached in this study. The first is that the origins of this anomaly are more complex than previously thought, with an anomalous atmospheric circulation contributing at least as much to the lack of open water as damming of sea ice by a large iceberg known as C-19. Only in the western RS, where C-19 lay, is damming found to restrict open water in the spring of 2002 (October–December), but even here the coldest spring in the last 15 years extended the sea-ice formation season. Elsewhere in the RS the divergent northward ice drift that normally occurs widely reversed to southward in early spring and was then followed by negligible ice motion. The most anomalous springtime ice drift occurred in the central and eastern RS rather than near C-19 and was mirrored in the weakest southerly winds on record in central areas.*

The unusual southward ice drift in early spring 2002 caused widespread convergence and compaction of the normally thin and undeformed first-year ice along and north of the central and eastern Ross Ice Shelf (RIS). Compacted ice with few leads would have been slow to melt in the warmest summer (January–February) months. Direct observations also indicate that sea surface temperatures (SSTs) rapidly fell to freezing in the central and western RS in February 2003 supporting new ice formation. All the available data indicate these were due to the cold spring and the extensive, compact ice cover in the late spring of 2002 and in January 2003 preventing most of the incoming solar radiation from reaching the ocean.

The second finding is that sea ice in the summer of 2003 would have been very extensive even if C-19 had not occurred. This is based on comparisons with other years of extensive summer ice, notably one when no large iceberg occurred. Ice motion and atmospheric circulation patterns in this case resembled those in the spring of 2002 and the summer of 2003. Evidence that the anomalous atmospheric circulation in the RS in the spring of 2002 was typical of El Niño events is also discussed.

RESUMÉ *[Traduit par la rédaction] On examine le rôle joué par la circulation atmosphérique dans l'étendue minimale record de l'eau libre dans la région polaire de la mer de Ross au cours de l'été austral 2003. Cette étude permet de tirer deux conclusions importantes. La première est que les causes de cette anomalie sont plus complexes qu'on ne l'avait d'abord cru, une circulation atmosphérique anormale contribuant au moins autant à la faible étendue de l'eau libre que le barrage de la glace de mer par un gros iceberg nommé C-19. C'est seulement dans la partie ouest de la mer de Ross, où se trouve C-19, que l'effet de barrage a limité l'eau libre au printemps 2002 (octobre à décembre) mais, même dans ce cas, le printemps le plus froid des 15 dernières années a allongé la saison de formation de la glace de mer. Ailleurs dans la mer de Ross, la dérive divergente de la glace vers le nord normalement observée s'est généralement inversée vers le sud au début du printemps pour ensuite être suivie d'une période de mouvement négligeable de la glace. La dérive printanière la plus anormale au cours du printemps s'est produite dans le centre et l'est de la mer de Ross plutôt qu'à proximité de C-19 et elle était le reflet des vents du sud les plus faibles à avoir été enregistrés dans la région du centre.*

La dérive inhabituelle de la glace vers le sud au début du printemps 2002 a provoqué une convergence et un compactage généralisé de la glace de première année normalement mince et non déformée le long et au nord des parties centre et est du plateau de Ross. La glace compactée avec peu d'ouvertures aurait donc fondu plutôt lentement au cours des mois d'été les plus chauds (janvier et février). Des observations directes indiquent aussi que les températures de la surface de la mer se sont rapidement abaissées jusqu'au point de congélation dans le centre et l'ouest de la mer de Ross en février 2003, ce qui a favorisé la formation de nouvelle glace. Toutes les données disponibles indiquent que ces basses températures sont dues au printemps froid et à la couverture de glace compacte et étendue à la fin du printemps 2002 et en janvier 2003, qui a empêché la majeure partie du rayonnement solaire incident d'atteindre l'océan.

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La deuxième conclusion est que la glace de mer à l'été 2003 aurait été très étendue même si C-19 ne s'était pas produit. On se base sur des comparaisons avec d'autres années de grande étendue de glace en été, notamment une année où il n'y a pas eu de gros iceberg. La configuration du mouvement des glaces et celle de la circulation atmosphérique dans ce cas ressemblaient aux configurations observées au printemps 2002 et à l'été 2003. On discute aussi d'indications selon lesquelles la circulation atmosphérique anormale dans la mer de Ross au printemps 2002 était typique des événements El Niño.

1 Introduction

A recent study (Zwally et al., 2002) of changes in Antarctic sea-ice cover over the last 25 years using high quality satellite-based estimates of ice extent showed ice extent in the Ross Sea (RS) (Fig. 1a) region increasing in all seasons of the year. Since the late 1990s there have been three exceptional summers (January–February) in 1998, 2001 and 2003 (see Arrigo and van Dijken (2003), hereafter AVD03: Fig. 1) when open water decreased appreciably in southern parts of the RS giving rise to the most extensive summer ice in the satellite record from 1979. This contrasts sharply with the Bellingshausen Sea east of the RS where a negative trend in ice extent has led to sea ice almost completely disappearing in some summers during the last 15 years (Zwally et al., 2002).

AVD03, found that the extent of open water in summer polynyas in the southern RS in the late 2003 austral summer (Fig. 1a) was only 25% of the long-term average. They highlighted some major ecological impacts of the extensive summer ice cover. By damping ocean swell, this extensive first-year ice also helped to keep intact the extensive fast ice, which was up to 3 m thick, in McMurdo Sound in the south-west RS, as far out as 50 km from the U.S. coastal McMurdo station (78°S; 167°E). This fast ice delayed the arrival of summer supply ships at the station, including a large oil tanker.

In order for extensive ice to occur in the warmest summer months in the RS, the spring ice cover must stay intact into the summer because surface air and ocean mixed layer temperatures at this time will usually be too high for ice to form (Arrigo et al., 1998). In the RS, divergent northward ice motion prevails as southerly winds advect ice from the south-east to north-west (Emery et al., 1997; Bromwich et al., 1998; Arrigo and van Dijken, 2004, hereafter AVD04). If the spring ice cover does stay intact this will have a cooling effect, helping to keep the ice cover in place, since the high albedo ice and snow reflect large amounts of incoming solar radiation. Extensive ice will also reduce the amount of thermal warming of the ocean mixed layer and thus reduce summer ice melt.

Arrigo et al. (2002) and AVD03 have linked very extensive ice in the RS in the summers of 1998 and 2001 to disruption of the usual divergent drift of pack ice in the preceding springs. AVD03 suggested that an anomalous atmospheric circulation reduced southerly winds and northward ice drift. In contrast, Arrigo et al. (2002) argued that the spring ice cover stayed intact mainly because a large iceberg dammed northward drift.

As in the spring of 2000, AVD03 proposed that the large 'C-19' iceberg (Fig. 1a) dammed large amounts of ice in the spring of 2002 to explain the lack of open water in the summer of 2003 (Fig. 1b). They suggested that the atmospheric circulation was not unusual at the time, at least in the western RS where C-19 lay. They noted this might have been because the El Niño event of 2002 was weakening at this time. In contrast, AVD03 linked extensive ice in the summer of 1998 to a strong El Niño. These studies suggest that in some El Niño events, the disruption of the normal divergent ice drift by an anomalous atmospheric circulation may be sufficient to ensure that large amounts of the spring ice cover stay in place until summer. If large icebergs therefore coincide with an anomalous atmospheric circulation they may only exacerbate disruption of the divergent ice drift. This may thus also have been the case in the spring of 2002 when another El Niño occurred (AVD03).

This study addresses three questions. Firstly, did an anomalous atmospheric circulation in the RS contribute to the ice cover in the spring of 2002 staying intact into the following summer? Secondly, why did the limited open water present early in the summer of 2003 disappear so rapidly in February of 2003 (Fig. 1b, AVD03, Fig. 2d) resulting in the record minimum open water extent at this time. Thirdly, would an extensive ice cover have occurred in the summer of 2003 if the C-19 iceberg had not occurred? It will be shown that the RS atmospheric circulation in the spring of 2002 resembles other El Niño events. The results obtained are used to ascertain if C-19 only exacerbated what would have been an anomalously extensive ice cover due to an unusual atmospheric circulation.

The analysis is in three parts. In the first, sea-ice cover, sea-ice motion and the atmospheric circulation in the RS in the spring of 2002 and summer of 2003 are examined to determine how far ice-atmospheric circulation interactions kept the RS ice covered and contributed to the closure of open water in February 2003. The role of surface winds in disrupting ice divergence and in ice compaction is discussed. Supporting evidence from other regions is also noted. In the second part, comparisons are made to other cases of extensive summer ice with and without large icebergs in the RS to determine if extensive ice could have occurred in the summer of 2003 had C-19 not occurred. Finally, the RS atmospheric circulation in the spring of 2002, when a moderate but weakening El Niño occurred, is compared to that of springs during other El Niños to determine if the event of 2002 was typical or atypical of these events.

2 Method

a *Ice Extent and Ice Motion*

Ice concentration (IC) fields for the Southern Ocean derived from satellite passive microwave measurements on a daily, or

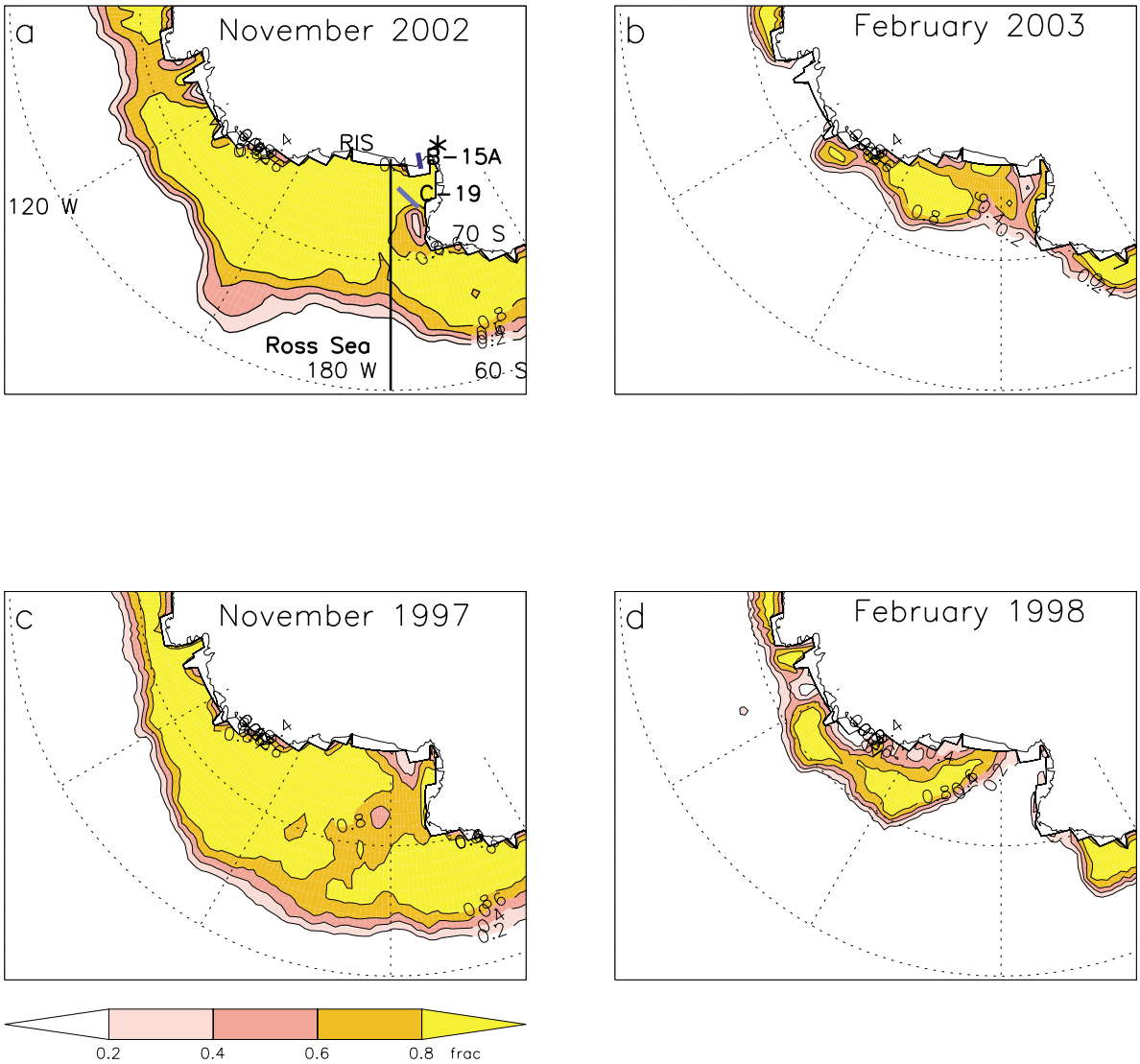

Fig. 1 Ross Sea monthly average ice fractions for (a) November 2002 and (b) February 2003 and (c) and (d) for the same months in 1997 and 1998. Positions of icebergs 'B-15' and 'C-19' in November 2002 are marked by short thick bars. McMurdo station is marked by an asterisk, RIS is the Ross Ice Shelf and the dateline is highlighted. B-15 was stationary and C-19 only moved slowly northwards after November 2002. Ice concentration is expressed as a fraction, where 1 indicates complete ice cover, 0.5 is 50% ice cover.

every other day, basis have been used to estimate monthly and seasonal ice extent (IE) and ice motion (IM). Zwally et al. (2002) discuss the data and the widely-used method to obtain IC. Routinely produced IC fields from the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center of the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) are used here. Their resolution is 0.5° latitude × 0.5° longitude.

A dataset of monthly average IM fields for 1987–2003 from the National Snow and Ice Data Center (Emery et al., 1997; Fowler, 2003) has been used to quantify ice-atmosphere interactions. This dataset is based on tracking ice 'displacements' detected in sequential 37 and 85 GHz satellite passive microwave data. The displacements are derived from the Special Sensor Microwave Imager (SSM/I) of the U.S. Defense Meteorological Satellite Program (DMSP). These SSM/I data are the most useful for detailed studies (Heil et al., 2001) because of their high spatial resolution (25 km) and their daily availability. Fowler (2003) noted that at least 20 separate ice vectors were used to obtain a monthly average value for a given pixel. The IM data were mapped to the same grid as the IC.

b *Winds*

This study uses monthly average 10 m *U* and *V* wind component fields from the reanalyses from NOAA/National Centers for Environmental Prediction (NCEP) for 1979–2003 (Kalnay et al., 1996), the European Centre for Medium-range Weather

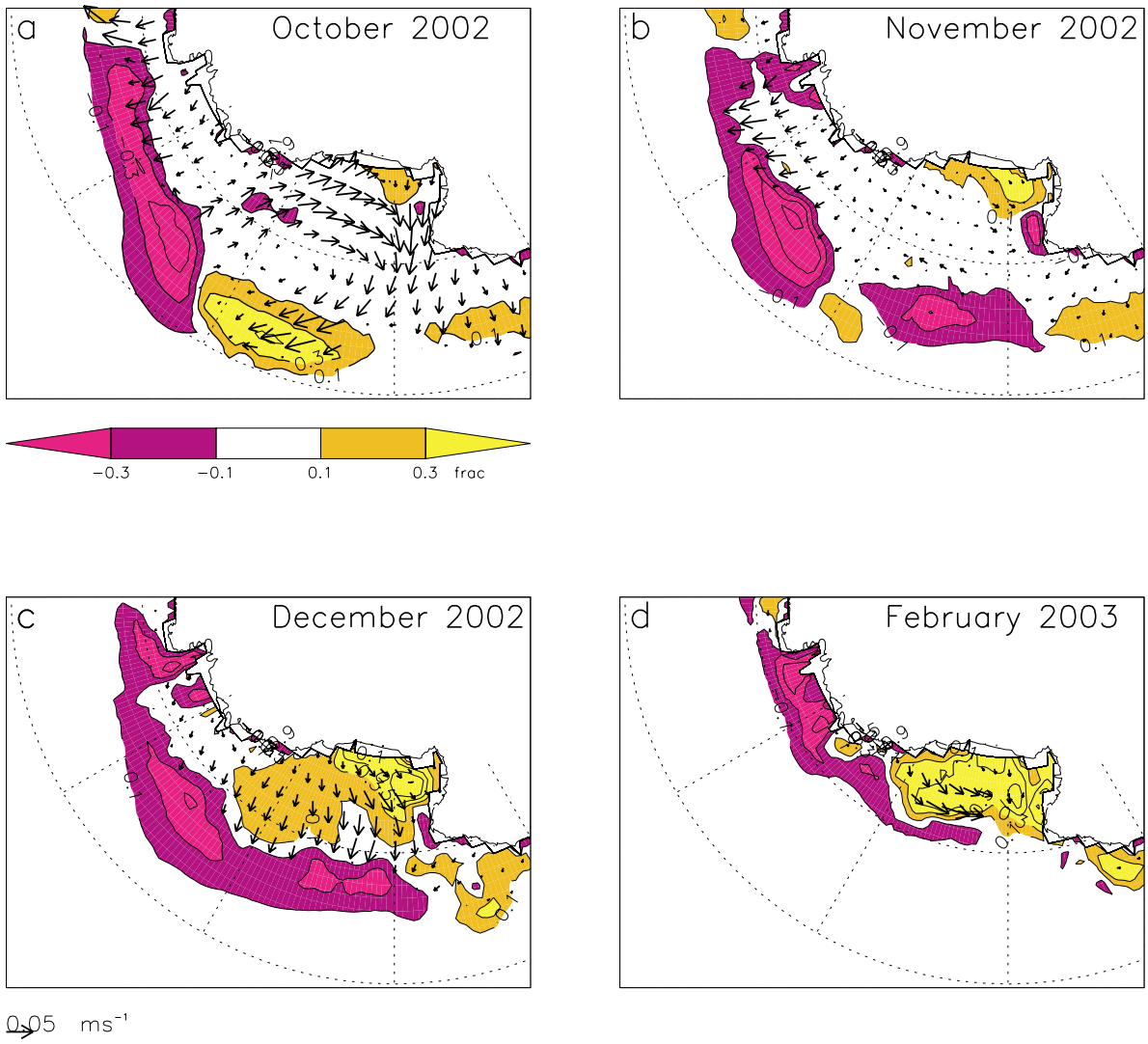

Fig. 2 Ross Sea monthly average ice motion vectors (m s^{-1}) and monthly ice fraction anomalies for October–December 2002 (a–c) and February 2003 (d).

Forecasts (ECMWF), referred to as 'ERA-40', for 1979 to 2001; and ECMWF operational (ECMWF-OP) analysis data thereafter (see http://www.ecmwf.int/research/era). Marshall and Harangozo (2002) compared station mean sea level pressure (MSLP) with NCEP data to show the generally high quality of the analyses since 1979. However, some discrepancies have been found in more recent data (Marshall, 2002). Renwick (2004) noted good agreement between the NCEP and ERA-40 daily sea level pressure (SLP) fields. Since all the results discussed in this paper are reproducible from both datasets only NCEP data are shown, with the exception of Fig. 8 for reasons discussed below.

c *Data Analysis*

The monthly average IC, IM and wind fields have been compared for the spring of 2002 and summer of 2003 to ascertain the atmospheric circulation impacts on ice extent. Evidence of an anomalous atmospheric circulation strongly altering IM and the resulting ice distribution in the spring of 2002 and the following summer is shown and discusssed. In order to do this, anomalies of IC, wind and IM from their long-term means have been obtained for individual months and for the spring (October–December). Long-term means of each quantity have been calculated for 1979–2002 except for ERA-40 data that are only available for 1979–2001. Positive IC anomalies indicate less open water than usual.

3 Sea ice conditions and atmospheric circulation in the summer of 2002/03

a *Ice and Open Water*

In October (not shown) and November 2002 (Fig. 1a) open water was negligible in the southern RS. In December (not

shown) it was limited to two areas west of the dateline near the western Ross Ice Shelf (RIS) and north of C-19. Open water peaked in January 2003 (not shown) but quickly disappeared in February (Fig. 1b). In February 2003 the extent of ice with an IC greater than 50% in the central RS, 165–180°W, was the highest in the high quality passive microwave record from 1979.

In October 2002, a positive IC anomaly developed along, and north of, most of the RIS (Fig. 2a) extending north to 73°S west of the dateline. Further north in this area a negative IC anomaly occurred. Similar features occurred in November (Fig. 2b) but in December (Fig. 2c) the positive anomaly intensified and extended across most of the southern RS. IC anomalies in January 2003 (not shown) closely resembled those in the previous month but positive anomalies became even more extensive in February (Fig. 2d) reaching 72°S in places.

b *Ice Motion*

Throughout the spring of 2002 and summer of 2003 northward IM occurred in the western RS west of the dateline (Figs 2a–d) but it was very weak in November 2002 (Fig. 2b). Elsewhere IM varied. In October 2002 (Fig. 2a) an average cyclonic IM centred at 165°W, 70°S advected ice south as far as the eastern and central RIS. Here the ice drift decelerated implying net ice convergence. In November ice was slow-moving throughout the RS and motion was negligible east of 165°W, including near the RIS. In December (Fig. 2c) ice drifted north-westwards, on average, west of 165°W but the drift was negligible near the RIS. In January 2003 (not shown) ice mostly drifted east–west near the RIS but north-westward further north. In February (Fig. 2d) an average westward ice drift also prevailed east of the dateline but it was northward around the dateline. IM was again negligible near the central and eastern RIS in this month.

c *The Atmospheric Circulation*

In October 2002 an average area of low pressure was centred in the RS (Fig. 3a). The winds at 10 m were northerly east of 160°W but southerly west of the dateline. In November (Fig. 3b) winds were very light over most of the RS because of a broad, weak trough of low pressure. Southerly winds also diminished in the western RS, notably east of 170°E. Light southerly winds continued to be widespread in December (Fig. 3c) but south-westerlies occurred further west. Winds were lightest near the central and eastern RIS, again because of a weak, broad trough of low pressure. Light south to south-westerly winds continued in January (Fig. 3d) but these returned to normal in February (Fig. 3e) around, and west of, the dateline.

4 Impact of the atmospheric circulation and C-19 on ice extent

a *Spring of 2002*

The IC and IM data indicate that other processes besides damming by C-19 kept the western RS and areas further east ice covered while C-19 moved quickly north up to November 2002 (AVD03) and afterwards. In the western RS, AVD03 attributed extensive ice in the 2003 summer to C-19 damming the prevailing north and north-westward drift of ice in this area in the spring of 2002. Figures 1a, 2a and 2b partly support this view; they show that a positive IC anomaly developed south of C-19, i.e., less open water than normal, and a negative anomaly developed to the north in October and November. However, two features are difficult to relate to damming by C-19. Firstly, C-19 moved rapidly north at around 3.2 km d^{-1} until late November (AVD03) so that some open water should have appeared in the western RS in the spring of 2002. However, open water only appeared south of C-19 in December and only near the western RIS (see AVD03: Fig. 2c). Also, an extensive positive IC anomaly developed and intensified along, and north of, most of the RIS even as C-19 moved quickly north, up to late November (AVD03).

In the western RS two further observations suggest that other processes reduced ice drift in November and contributed to extensive ice through spring:

- The mean northward drift of ice south of C-19 in the spring was only slightly below normal (Fig. 4a and see below).
- The weakest northward ice drift south of C-19 during the spring of 2002 (and summer of 2003) occurred in November, despite C-19 moving quickly north.

In the central and eastern RS two other observations indicate that other factors kept the ice cover in place:

- Extensive south-westward ice drift around, and east of, the dateline in October, along with weaker northward ice drift in the eastern RS than occurred around the dateline in November.
- Widespread lack of IM in the RS in November and in the southern RS in December.

It has been noted that C-19 could have exacerbated rather than caused the extensive ice in the RS. The reversal of the prevailing northward ice drift in the eastern and central RS in October 2002 indicates that this was the case because it indicates that damming of ice was not required to keep the ice cover intact. An explanation is now sought for the above IM features to determine if an anomalous atmospheric circulation was key to the ice cover in the spring of 2002 remaining intact into summer.

1 SURFACE WIND – ICE MOTION RELATIONSHIP

It is known that southerly and northerly winds frequently accompany ice extent increases and decreases respectively on sub-monthly timescales in the RS and other Antarctic regions (Harangozo, 2004). Average spring IM for 1987–2002 has been correlated with the 10-m seasonal average winds from the reanalyses to determine to what extent springtime ice drift

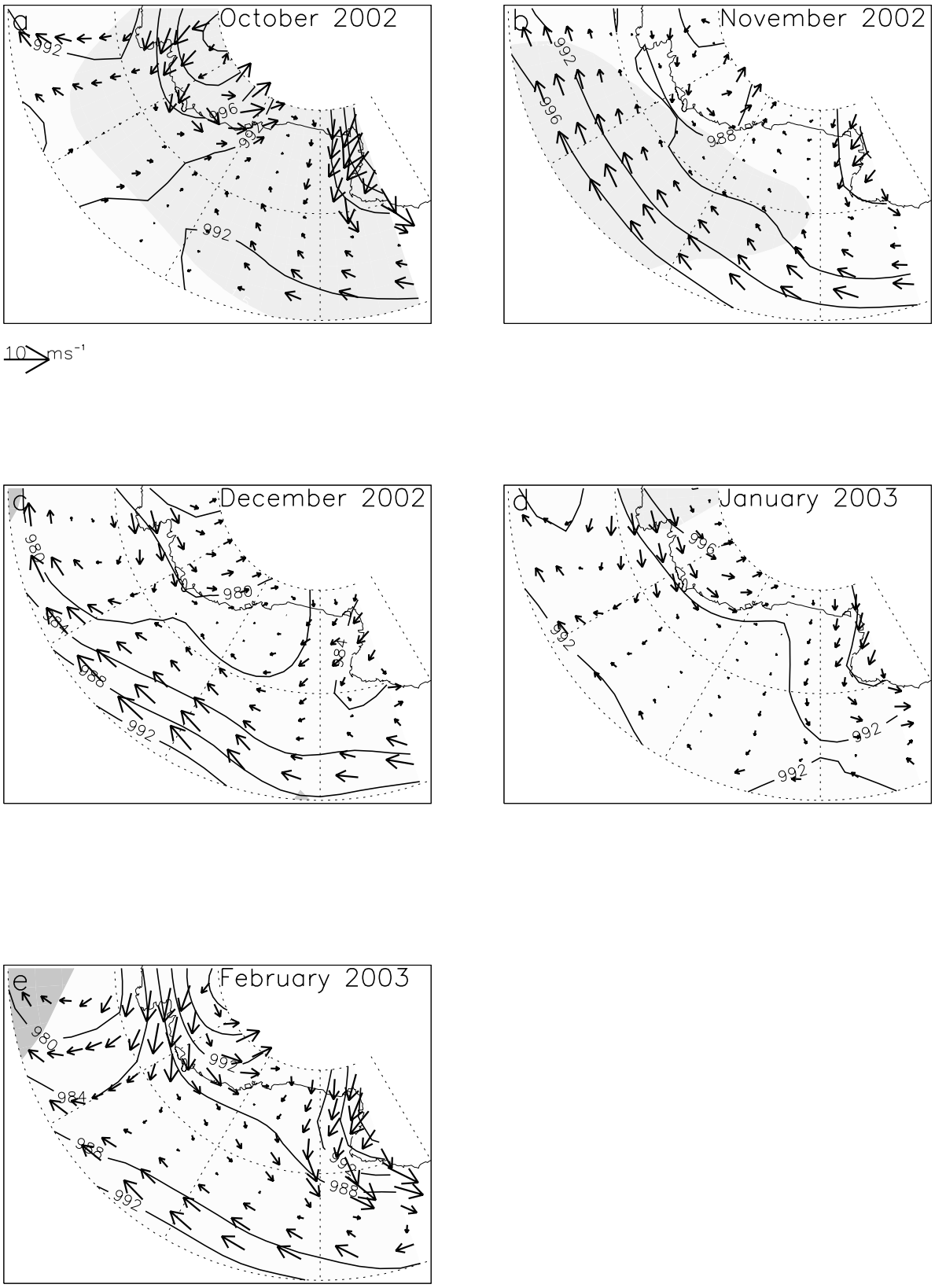

Fig. 3 NCEP monthly average SLP (hPa) (solid line) and10-m vector winds (m s^{-1}) for October–December 2002 (a–c) and January and February 2003 (d–e). Shading indicates SLP more than 1.5 s.d. above (light shading) or below (dark shading) the long-term mean.

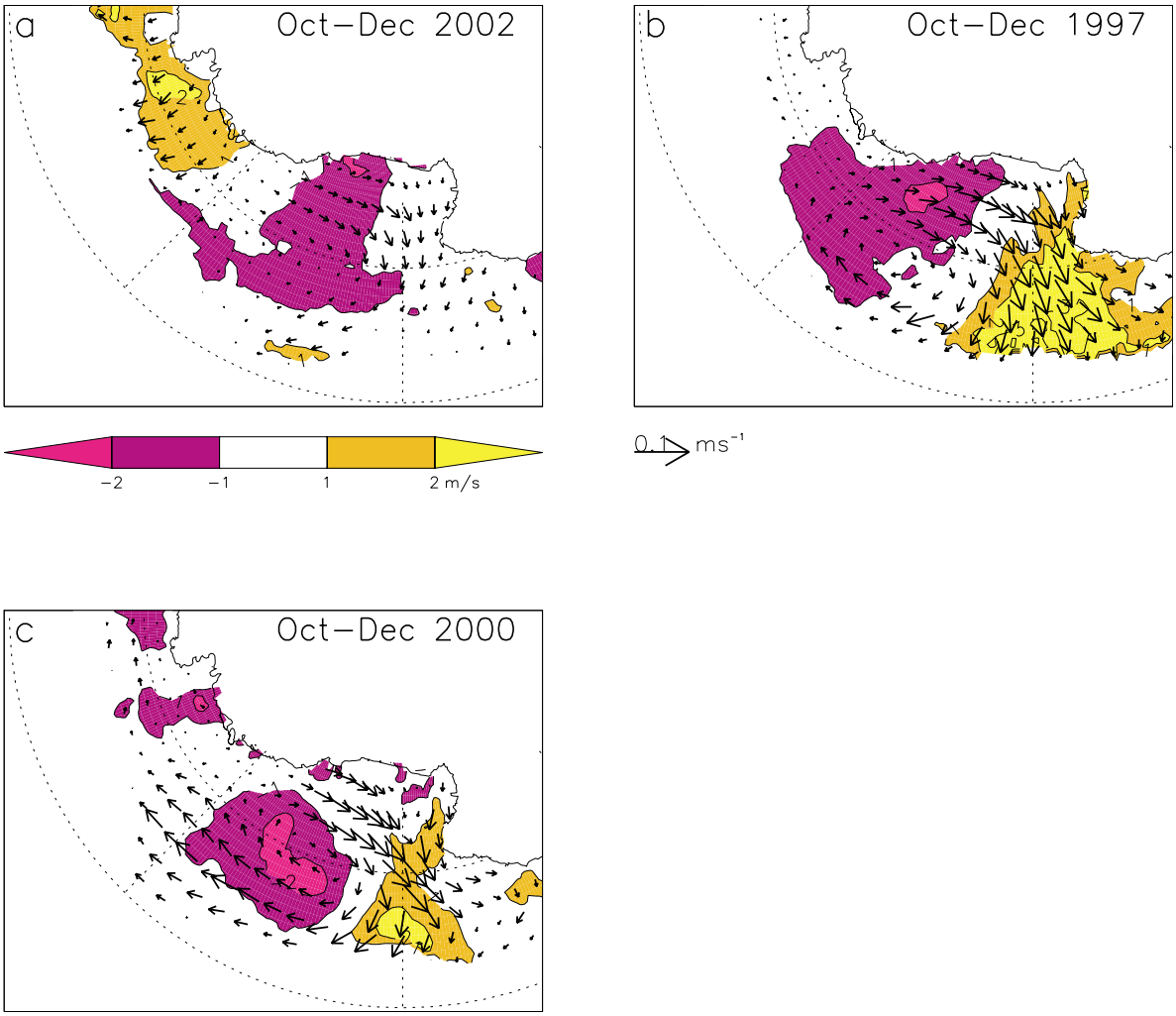

Fig. 4 Spring (October–December) average ice motion vectors (arrows) and standardized departures (shaded) of the seasonal average *V* component of ice motion from the 1979–2002 mean in (a) 2002, (b) 1997 and (c) 2000. Dark shaded areas indicate below normal northward ice drift.

responds to the atmospheric circulation. If, as is the case, a strong correlation exists this would indicate that northward ice drift in the RS weakens as southerly winds decrease or reverse. The seasonal average *U* and *V* components of IM and 10-m winds have been correlated for all springs excluding 2002 and 2000 when another large iceberg occurred (see Section 6b), and also just excluding 2000. The central RS region around 76°S, 170°W is examined in detail.

For the *V* component of IM and wind the correlation is 0.65 for NCEP and 0.36 for ERA-40/ECMWF-OP. If 2002 is included, however, the correlations increase to 0.76 and 0.53 respectively. For the *U* component, ERA-40 yields the best correlations: $r = 0.72$ for the entire dataset and 0.76 if 2002 is excluded. The NCEP(ERA-40) correlations for *V* for 1987–2002 are statistically significant at the 1% (5%) level using a Student's *t*-test.

These results indicate that winds do systematically modify ice drift in the central RS during austral spring. Clearly, 2002 was no exception to this thus indicating that the anomalous spring IM was significantly affected by the atmospheric circulation. The interrelationship of ice extent, ice drift, ice formation and winds in the RS during the spring of 2002 will now be looked at closely to assess the extent to which the atmospheric circulation kept the spring ice cover intact.

2 ANOMALOUS ICE DRIFT IN THE SPRING OF 2002

The widespread southward ice drift in October followed by a very slow moving ice pack over the entire RS in November and, at least along and near the entire RIS, in December, indicates that damming of ice by C-19 was not needed for the central and eastern RS to stay ice covered until the end of 2002. In particular, southward ice drift to the central and eastern RIS area in October 2002 has only occurred in a small number of spring months in the high quality SSM/I record. Some of these are discussed below.

This southward drift would have contributed to the spring ice cover staying intact in three ways. Decelerating and converging ice along, and north of, the central and eastern RIS

would have extensively compacted and thickened the main ice pack. Arrigo et al. (1998) point out that the RS ice pack in spring is susceptible to dynamic modification by winds because rising air temperatures increase brine volume which reduces the tensile strength of the ice. It follows, however, that ice compaction and compression would then increase the ice strength. Other evidence of substantial ice compaction and compression occurring when ice drifts towards the Antarctic coast is noted in Section 5. Moreover, southward drift of the main ice pack would also have extensively rafted and ridged the thin first-year ice around the RIS. Coastal Antarctic sea ice is often thin because large amounts of ice form in polynyas maintained by the divergent offshore winds (Bromwich et al., 1998).

These processes would have produced a large 'plug' of compacted, compressed, and thus strengthened, ice along and near the RIS. This has two implications. Firstly, the plug would have been slow to break up because of its increased internal ice strength. Secondly, because of its size and strength, the plug would have been slow moving once north to north-westward drift returned with C-19 lying in its path (Fig. 1a). Indeed, Figs 2a and 2b confirm that north-westward drift did return along and near the central RIS in December but that it was very weak. Other indirect evidence for the formation of plugs of compacted ice during other springs is noted in Sections 6a and 6b. Their slow-moving nature, even when no large icebergs occur and in spite of strong southerly winds, is highlighted.

A compact and perhaps thicker ice pack along and near the RIS in the spring of 2002 is consistent with the record extent of ice with a concentration higher than 50% in the central RS during February 2003 noted above. However, a causal link requires the spring ice cover to have stayed largely in situ into the summer of 2003. Figure 4a supports this, showing the northward component of ice velocity in the central RS (~170°W, 76°S) was 1.6 standard deviations (s.d.) below normal during the spring of 2002. Along the central RIS it reached 2 s.d. below normal. There is no similar reduction in the northward component of ice drift near the central RIS in spring in the high temporal resolution SSM/I record. Most striking, is the disappearance of northward drift in the central RS in November 2002 (Fig. 2b) that also only occurs in a small number of spring months in the SSM/I record, these being highlighted below. As noted in Section 4b1ii, heavy compaction of the spring ice pack would also have reduced ice loss through melting during the summer of 2003.

3 ICE FORMATION

It has been noted that the south-west RS was devoid of open water during October and November 2002 despite C-19 moving rapidly north at the time and there being little westward drift of ice toward the western RS (Figs 2a–2c). A possible explanation is that ice continued to form into the late spring here. Arrigo et al. (1998) showed that the appearance of the RS polynya in spring is delayed if unusually cold conditions prevail in the region.

Data from McMurdo station in the south-west RS indicate that the monthly average surface air temperature in October 2002 was -16.7°C, -10°C in November and –4.6°C in December. The springtime average temperature of –10.4°C was the lowest since 1988 (no data exist for December 1999 but October and, in particular, November 1999 were warmer than in 2002). It is not clear why these cold conditions occurred. Both the NCEP reanalyses and ECMWF-OP analyses indicate southerly winds from the continent were near or below normal in the western RS in the spring (as noted in the next section). Clearly, however, air temperatures in this part of the RS were low enough for ice to continue forming into late spring.

Contrary to previous work, temperature observations and ice drift patterns during the spring of 2002 thus indicate that the western RS remained ice covered during the spring of 2002 only partly because of damming of ice by C-19. Attention now turns to the atmospheric circulation during the spring of 2002 and how this affected the unusual sea-ice drift patterns.

4 ATMOSPHERIC CIRCULATION IMPACTS

AVD03 suggested that the atmospheric circulation in the western RS in the spring of 2002 was not unusual but Figs 3a–3c and Fig. 5a show that prevailing southerly winds were weaker than normal over most of the RS, and very weak east of the dateline. It has also been noted that northward ice drift in the western RS in November was weak despite C-19 moving quickly north at the time. On the other hand, a large reduction in southerly winds occurred in November (Fig. 3b) compared to October (Fig. 3a). Southerly winds in the western RS were 1.5 s.d. below normal in November. Three processes – damming, freezing and, for a time, decreased northward ice drift owing to weak southerly winds – thus ensured that the western RS remained, for the most part, ice covered until the summer of 2003.

Little or no ice damming was needed to keep the plug of compact ice intact after it formed in October 2002. The most striking wind anomalies occurred along and near the central and eastern RIS in November 2002; the NCEP reanalyses (Fig. 3b) and the combined ERA-40/ECMWF-OP record indicate that the monthly average meridional wind was close to, or at, zero in the central RS. This was 2.5 s.d. below the November average. The negligible northward ice drift along the central and eastern RIS for spring (Fig. 4a) was mirrored by the seasonal southerly wind component being up to 2 s.d. below normal (Fig. 5a) and near zero along, and near, the central RIS. This is the only such case in this area of the RS in the NCEP record since 1979. The ECMWF-OP data indicate an average northerly wind in this location in the spring of 2002.

Contrary to AVD03, an anomalous atmospheric circulation rather than damming by C-19 therefore ensured that the ice cover remained intact along, and near, the central and eastern RIS into the summer of 2003. Further evidence that a plug of compact ice was crucial to the spring ice cover remaining

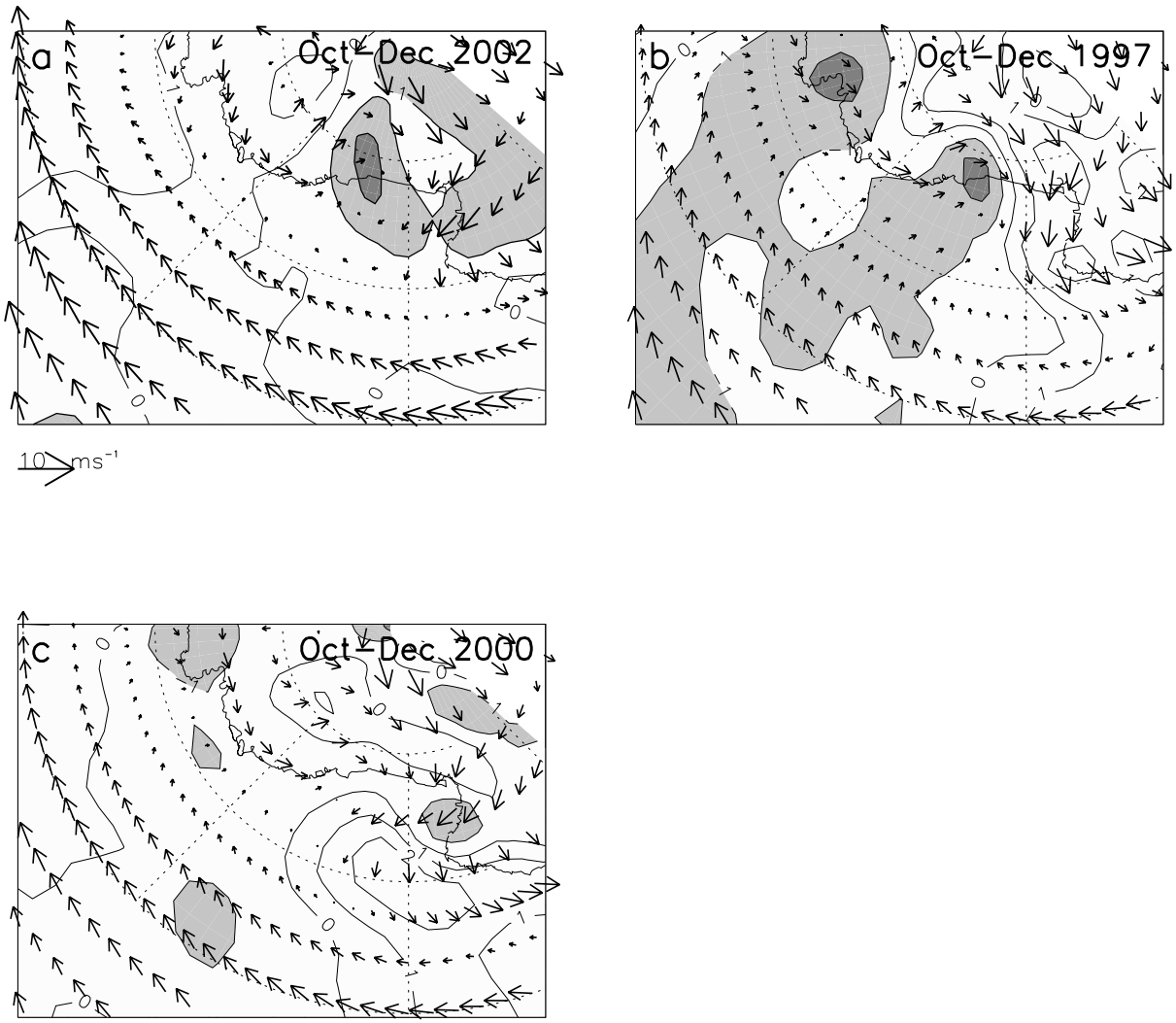

Fig. 5 Spring average 10-m wind (m s^{-1}) (vectors) and standardized departures of the seasonal average *V* component of the 10-m wind (shaded) from the 1979–2002 mean in (a) 2002, (b) 1997 and (c) 2000. Light (dark) shading indicates meridional winds 1(2) standard deviations below normal.

intact into the summer of 2003 is discussed in Sections 6a and 6b. Attention now turns to the factors that contributed to the lack of open water in February 2003.

b *2003 Summer*

It has been noted that the explanation for the lack of open water in February 2003 must also address why the spring ice cover persisted during the warmest months and why open water quickly disappeared during this month.

1 PERSISTENCE OF EXTENSIVE ICE

i ***Damming and ice divergence***

Some damming of ice continued south of C-19 (south of 76°S) during January and February 2003; northward ice drift was weak during these months, including February (Fig. 2d) when southerly winds returned to normal (Fig. 3e). Elsewhere in the RS, light southerly winds continued during the summer of 2003. In January (Fig. 3d) the monthly average southerly wind was generally 1 s.d. below normal. Northward ice drift in the central RS during this month (not shown) was also the second lowest after 1998 (see Section 6) during the five years when some of the spring sea-ice cover persisted into January.

ii ***Limited melting***

The retention of a compact ice cover with high albedo from spring would have reduced any ice melting. Reports from the R/V *Nathaniel B. Palmer* (see University of Wisconsin web site; ftp://ice.ssec.wisc.edu/pub/shipobs) in the central RS about the dateline in February 2003 confirm that first-year ice floes of 1–2 m and 4–6-tenths IC were widespread between 73°–76°S. The small size and/or number of leads would also have limited thermal warming of the upper ocean through absorption of solar radiation. In turn, this would limit the positive feedback process whereby ocean warming results in

more ice melting and the greater amount of exposed ocean then absorbs even more shortwave radiation causing more melting.

2 EARLY CLOSURE OF OPEN WATER

Figure 2d in AVD03 shows that open water in the south-west RS closed for a few weeks in February. Noting that C-19 was at its most northerly position at this time (AVD03), any damming should have been further north. The closure also occurred despite near-normal southerly winds returning in the western RS (Fig. 3e). The satellite sea-ice record from 1979 shows no other summer when open water disappeared in February. The most likely explanation is that new ice formed at this time.

Routine, six-hourly observations from the R/V *Nathaniel Palmer* cruise confirm widespread new ice in the central and western RS south of 73°S after the 10 February, i.e., the same time satellite data show open water areas starting to close (AVD03, Fig. 2d). The ship reports, mainly made between 175°E–170°W, indicate 2–4-tenths of new or grey ice and thin first-year ice, 30–60 cm thick, were widespread from this time. By the 20 February 6–8 tenths of ice cover was regularly reported and almost complete coverage occurred soon after.

The R/V *Nathaniel Palmer* reports also confirm that sea surface temperatures (SSTs) were often around, or close to, freezing (about –1.8°C) after 10 February. Before mid-month, however, air temperatures at the ship were generally above –8°C, the threshold at which ice formation is observed to occur in the Weddell Sea (Limbert, 1968). Therefore, new ice reported before mid-month must have drifted north from colder areas close to the RIS. After mid-month, however, air temperatures around the R/V *Nathaniel Palmer* frequently dropped to –8°C or lower indicating ice formation was spreading northward.

The question remains, why did SSTs approach the freezing level by the second week of February 2003? There are three possibilities: unusually cold air temperatures, cold advection in the ocean, or a pre-existing cold ocean thermal anomaly caused by the ice cover remaining mostly intact from the spring of 2002. Any freshening of the ocean in the southern RS from the melting of C-19 would have been very limited because C-19 lay furthest north at this time and strong currents in the western RS (AVD03) would have quickly advected fresher water north. Unusually low air temperatures did not occur during summer; the monthly average temperature at McMurdo station in the south-west RS in February 2003 was –8.4°C but similar, or lower, temperatures occur during many other Februarys with little or no sea ice. The R/V *Nathaniel Palmer* reported temperatures similar to McMurdo. The January 2003 average temperature at McMurdo, at –2.1°C, was also not unusual. On the other hand, the cold spring in the western RS would have kept SSTs depressed into the summer.

Cold ocean advection is also very unlikely. This should have supported more extensive ice than usual not only during summer but also during the preceding spring because ocean heat anomalies only move slowly in regions with generally weak currents, such as the RS. In fact, there was less ice than normal over much of the northern RS during the spring of 2002 (Figs 2a–2c).

This points to the freezing SSTs in February 2003 occurring because the persisent spring ice cover greatly limited the absorption of solar radiation in the ocean mixed layer during summer. Reports from the R/V *Nathaniel Palmer* in early February 2003 confirm that SSTs around 72.5°N–75°S, ~175°E were already at, or near, freezing around –1.4° to –1.8°C. Air temperatures were also dropping, being generally between –4° and –6°C, thus ensuring that SSTs stayed low.

Renfrew et al. (2002) showed that the southern Weddell Sea can warm considerably in summer but only if most of the spring ice cover has been advected out of the area. This is also the case in the Bering Sea (Hunt et al., 1999) and suggests that the mixed layer will only stay close to freezing in summer if the spring ice cover stays mostly intact. Figure 2d in AVD03 indirectly supports this interpretation, it shows open water in the RS closing earlier in late summer and early autumn as the appearance of open water in spring is delayed more. Since 1998, the first year of their study, AVD03 show that after 2003 the earliest date when open water started to disappear was late February in 1998 and 2001. These were also years when open water appeared late in the spring (see Sections 6a and 6b). Ultimately, however, the springtime disruption and reversal of the normal divergent ice drift by an anomalous atmospheric circulation and the extended freezing season ensured there was little ocean warming in the summer of 2003 and preconditioned the area for ice formation so early in 2003.

5 Atmospheric circulation impacts on unusual summer ice extent in other regions

Several case studies (Ackley et al., 2001; Renfrew and King, 2002; Turner et al., 2003) have attributed unusual summer open water extents in the Weddell Sea to anomalous atmospheric circulations that disrupt or enhance northward ice drift both in summer and the preceding spring. Ackley et al. (2001) and Renfrew et al. (2002) attributed the occurrence of a large summer polynya in one year to increased northward ice drift in the austral spring and early summer. They linked this to long periods of strong southerly winds during summer and the preceding spring. Conversely, Turner et al. (2003) attributed, in part, very extensive ice along the southern coast of the Weddell Sea during one summer to the disruption of northward ice drift at that time and during the preceding spring. As with the RS during the spring of 2002, they found persistent strong northerly winds over the Weddell Sea during the spring of 2001 and the following summer. The lack of northward drift ensured that the main ice pack remained near the south coast of the Weddell Sea.

Two studies have indicated that extensive compaction of spring Antarctic sea ice can occur over short periods of just a few weeks and linked this to more extensive ice than usual in the late spring and summer. The first study, by Turner et al. (2003), of the extensive summer ice along, and north of, the

southern Weddell Sea coast showed that a lack of northward drift of the main pack blocked the normal westward drift along the coast associated with the Weddell Sea gyre. Ship observations confirmed that extensive, compact ice persisted along the coast throughout the spring and summer. As with the RS during 2002, this resulted in positive IC anomalies developing in the late spring. Late spring and summer sea-ice conditions along the coast were so severe that an annual relief ship could not reach Halley station (75.5°S, 26.5°W) in early or late summer.

The second study (Massom, personal communication 2004) carried out during a science cruise in the Bellingshausen Sea in October 2001, observed widespread ice compaction and deformation with ice 15–20 m thick. In just one week this resulted in a 40% reduction in the regional ice extent due to ice compaction and compression from extensive southward ice drift, along with melting in the outer ice pack. Massom found extensive southward ice drift also occurred before this rapid retreat with an ice drifter buoy moving south 1° of latitude in Marguerite Bay during August–September 2001. As with the RS during the spring of 2002, very strong northerly winds occurred both during the retreat and the entire spring of 2001. As with the Weddell Sea case, the other similarity to the RS in 2002/03 was that heavy ice persisted into the late spring giving above normal IC near the west Antarctic Peninsula coast. Again, this is consistent with heavily deformed ice being difficult to remove through melting because of its compactness and lack of leads preventing solar radiation from warming the upper ocean.

Other Bellingshausen Sea studies have also found considerable ice compaction by southward ice drift during periods of strong northerly winds lasting up to a few weeks. In one case (Worby et al., 1996) a cruise in the winter pack ice, following widespread southward ice drift over two weeks, found very extensive deformed and thick ice (Turner et al., 2003). King (personal communication, 2004) has also reported ice compaction from southward ice drift causing substantial dynamical ice retreat during two weeks in early winter. Again, strong northerly winds induced a southward drift.

It is thus concluded that strong ice-atmosphere interactions were crucial to the record summer ice extent in the RS in 2003 with both extensive ice compaction and new ice formation being key processes. The last question posed in this study as to whether extensive ice could have occurred during the summer of 2003 if C-19 had not been present is now addressed. Comparisons are made to two other years of extensive summer ice in the RS and, in particular, one with no large iceberg. These provide further indirect evidence that ice compaction is crucial to the spring ice cover staying intact.

6 Comparisons to other years

There have been two other summers in the satellite passive microwave record with greatly reduced open water in the RS in 1998 and 2001. Unlike 2003, the lack of open water during summer in these cases was entirely due to the ice cover in the previous spring staying in place into the warmest summer months; Figure 3 in AVD03 shows that the open water areas did not start to close until very late in February in both years. Most attention is given to the spring of 1997 since the second lowest open water extent on record occurred in the summer of 1998 with no large icebergs (AVD03).

a *1997 Spring*

1 ICE DRIFT

It has been found that positive IC anomalies developed along and near the RIS during the spring of 2002 when the prevailing northward ice drift reversed to southward in this area. The spring of 1997 (Fig. 1c) is the same; Fig. 6b shows that positive IC anomalies did not develop until ice drifted south in November. In contrast, negative anomalies occurred in October 1997 (Fig. 6a). Again this southward motion would have compacted ice near the RIS. As in December 2002, very weak ice drift during December 1997 (Fig. 6c) helped to keep the ice cover intact. Consequently, northward drift along, and north of, the central and eastern RIS was generally 1–1.5 s.d. below normal during the spring of 1997 (Fig. 4b), the weakest in the high temporal resolution SSM/I record after 2002. Moreover, in the eastern RS southward drift during the spring of 1997 was the strongest on record since 1979.

Weak northward ice drift near the RIS continued into the summer of 1998 including February (Fig. 6d). As in 2002–03, positive IC anomalies that occurred in December 1997, intensified and spread in January 1998 (not shown). As in January 2003, this coincided with an average southward ice drift in the central RS (not shown).

2 ATMOSPHERIC CIRCULATION

As in 2002, the 1997 springtime atmospheric circulation (Fig. 5b) closely mirrored the ice drift, with very weak southerly winds in the central RS and northerlies in the eastern RS. The NCEP data indicate that springtime northerlies just north of the eastern RIS at 76°S, 160°W in 1997 were the second strongest after 2002 and vice-versa in the ERA-40/ECMWF-OP record. Southerly winds in the central RS during the spring of 1997 were the third weakest in both the NCEP and ERA-40 records since 1979.

These similarities between 2002 and 1997 confirm that the spring ice cover can persist into the summer when northward ice drift is greatly reduced along, and near, the RIS because of anomalous atmospheric circulation. The two differ mainly in that northward IM was stronger than normal around, and west of, the dateline in 1997 where, as expected, negative IC anomalies developed during spring. Stronger than normal southerly winds occurred here because of a stronger cyclonic circulation in the RS (Fig. 5b). As in the summer of 2003, however, weak southerly winds also occurred near the central and eastern RIS during the summer of 1998 (not shown).

This comparison indicates that the atmospheric circulation during the spring of 2002 and the summer of 2003 was optimal for sea ice to persist along, and near, the RIS because of

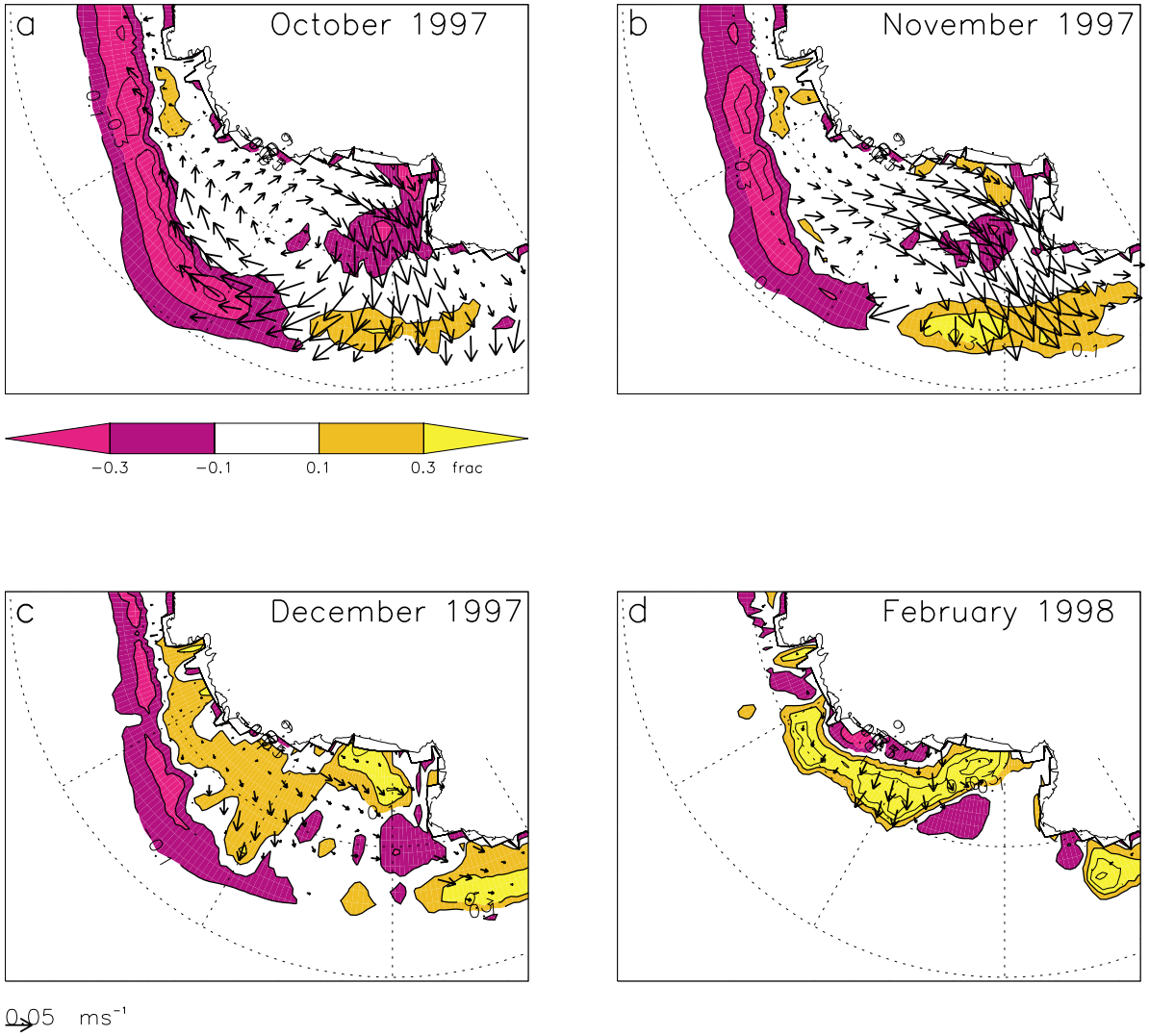

Fig. 6 As Fig. 2 but for October–December 1997 and February 1998.

northerly winds in the east and weak southerly winds elsewhere. In other words, a weak rather than strong cyclonic circulation, as in 1997, is most favourable for the retention of the ice cover because it reduces southerly winds in the central and western RS. Clearly, C-19 only exacerbated the severity of the ice conditions during the summer of 2003 by impeding northward ice drift in the western RS during the preceding spring. It is thus concluded that ice extent during the summer of 2003 would have been at least comparable to that in 1998 if C-19 had not occurred, and quite possibly greater.

b *2000 Spring*

Arrigo et al. (2002) indicated that damming of ice by the 'B-15' iceberg was appreciable during the spring of 2000, the iceberg and its fragments being oriented in a south-west/north-east line about the dateline. Figure 4c shows that the northward ice drift was weak along, and near, the central and western RIS during the spring of 2000. Northward drift was also negligible about the dateline to about 74°S, this being weaker than occurred in either the spring of 2002 or 1997. In contrast, Fig. 5c shows that southerly winds were only slightly below normal near the RIS and around the dateline during the spring of 2000.

These observations partly fit the view of Arrigo et al. (2002) that damming of ice was appreciable during the spring of 2000 but two features also implicate the atmospheric circulation in the spring ice staying intact into the summer of 2001. Firstly, despite the presence of the iceberg, strong northward ice drift occurred east of the dateline during October 2000 and negative IC anomalies widely occurred around and west of the dateline. Secondly, the appearance of positive IC anomalies in November along, and north of, the central RIS (Fig. 7b), including to the south and east of the B-15 icebergs, again coincided with widespread southward drift. As in October 2002, this southward drift sharply decelerated north of the central RIS and east of the line of icebergs. This

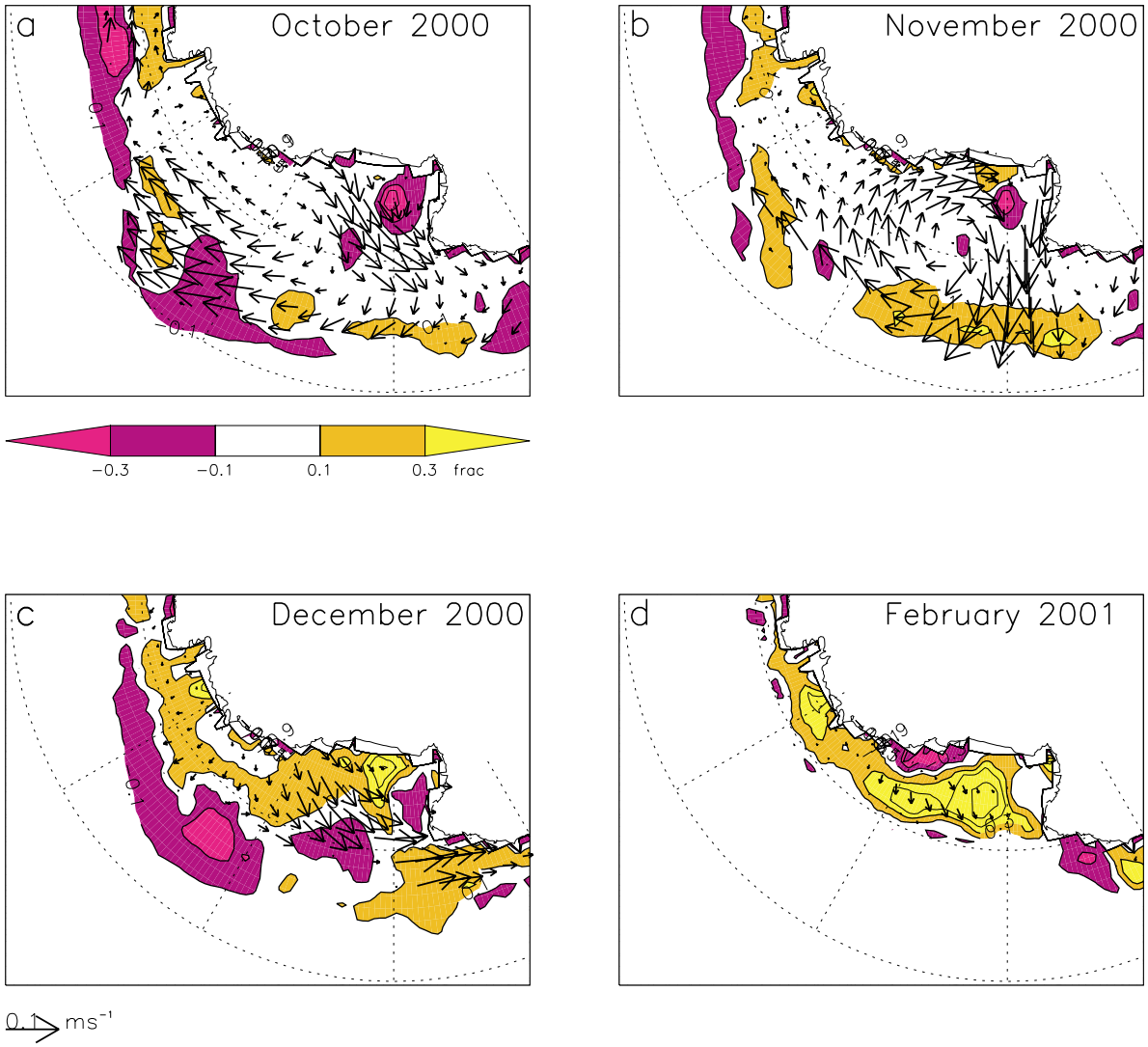

Fig. 7 As in Fig. 2 but for October–December 2000 and February 2001.

pattern of positive anomalies developing only when there is widespread southward ice drift thus mirrors the spring of 1997 (Fig. 6). Strong north-easterly winds occurred in the eastern and central RS in November 2000 (not shown). Moreover, the positive IC anomaly intensified and became extensive in December (Fig. 7c).

These observations again point to anomalous southward ice drift being the key to positive IC anomalies developing along and near the RIS; in all three cases in this study, southward drift decelerated approaching the RIS. As in October 2002, widespread ice convergence and compaction in November 2000 would have produced a large 'plug' of compacted ice around the RIS. In sharp contrast to October 2000 this would then only have been able to move slowly as northward drift returned in December 2000 (Fig. 7c) because of B-15 lying downstream. Based on these intercomparisons, strong ice-atmosphere interactions thus, at least to some extent, kept the ocean ice covered east of B-15 into the summer of 2001.

7 The 2002 El Niño event and the RS atmospheric circulation

Lastly this study considers whether the RS atmospheric circulation in the spring of 2002 (Fig. 5a) was typical of El Niño events. A composite or 'superposed epoch' analysis was used to determine if there are statistically significant changes in the average 10-m meridional wind during El Niños compared to climatology. Seven El Niño events are included in the composite, including 2002 and 1997. The other events are listed in Trenberth (1997). In the analysis, the ERA-40 and ECMWF-OP record is preferred to the NCEP reanalyses in which the representation of the Pacific tropical atmospheric circulation is poor (Newman et al., 2000).

Figure 8 shows a statistically significant reduction (using a Student *t*-test) in the climatological mean southerly wind in the eastern and central RS between 155° and 169°W during El Niño events. Here, southerly winds are 0.5–0.6 m s^{-1} below normal. Comparing Fig. 8 to Figs 5a and 5b shows that the reduction in the southerly winds in the eastern RS during the

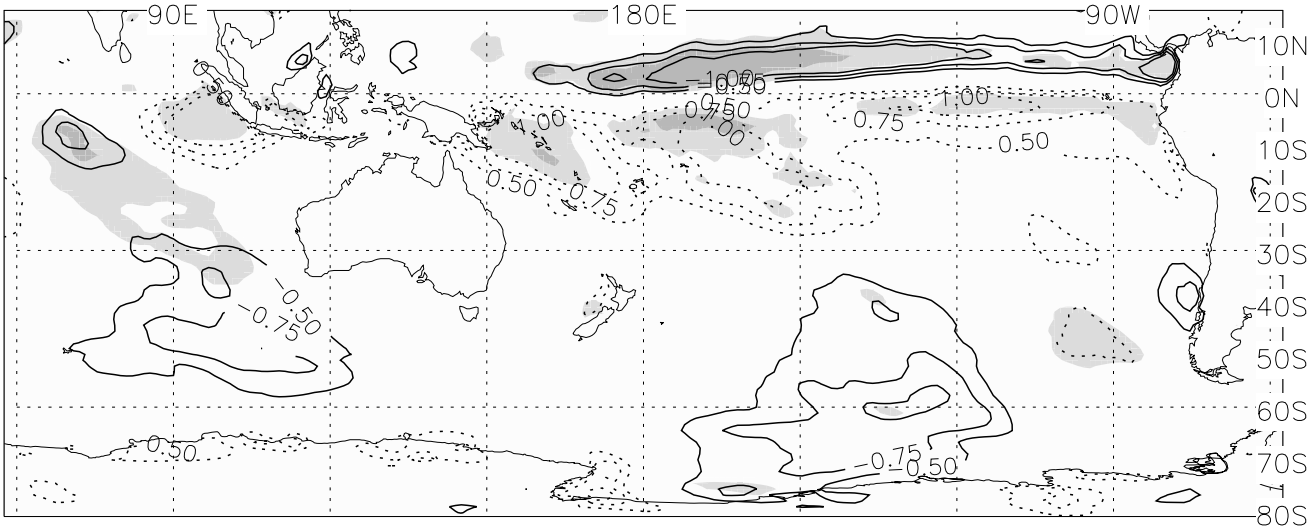

Fig. 8 The composite spring (October–December) ERA-40/ECMWF-OP 10-m meridional wind anomaly (m s^{-1}) for El Niño events from 1979–2002 (see text). Negative anomalies, indicating a reduced (increased) southerly (northerly) wind component, are shown by solid contours and the light (dark) shaded areas are statistically significant at the 5% (1%) level.

spring of both 2002 and 1997, when another El Niño occurred, was typical of these events.

AVD03 suggested that the 2002 El Niño was not reflected in the RS atmospheric circulation but this is clearly not the case. Their focus, however, was on the western RS, i.e., not the area where the statistically significant weakening of southerly winds during El Niños occurs. As far as is known, this is the first statistically significant atmospheric circulation change to be reported for El Niño events in the RS sector of Antarctica. This is not entirely surprising because previous studies (e.g., Trenberth and Caron, 2000) relied on shorter time series or fewer El Niño cases. It is noteworthy that AVD04 obtained a strong positive correlation between the RS multi-season average extent of open water during the period of October to early May, i.e., including the austral summer months, and El Niño-Southern Oscillation (ENSO) index in the 12-month July–June period.

Two other facets of the RS atmospheric circulation during El Niño events are also evident. Firstly, El Niño events such as the one in 2002 do not have to be unusually strong for an atmospheric circulation like that in the composite mean for these events to occur. The key feature of the spring of 2002 was the weak cyclonic circulation in the RS. In contrast, some strong El Niños are associated with very strong cyclonic circulation in the RS, as in 1997, when more ice was advected out of the western RS in spring than in 2002. Secondly, strong El Niños are not always accompanied by strong cyclonic circulation. The 1982 El Niño (not shown) is a case in point; southerly winds in the RS were about normal in both the NCEP and ERA-40 reanalyses in the spring of 1982, as was sea-ice extent at the time and during the summer of 1983. The natural variability of the atmospheric circulation may account for some differences between events. The RS atmospheric circulation during the springs of both 2002 and 1997 was thus fairly typical of El Niño events. This supports the conclusion that RS sea-ice extent during the summer of 2003 would have been at least as great as in 1998 if C-19 had not occurred.

8 Conclusions

It has been found that the lack of open water during the summer of 2003 cannot be adequately explained without taking into account an anomalous atmospheric circulation during the previous spring. This greatly perturbed the normal ice drift patterns with resulting widespread ice convergence. A prolonged freezing season also helped to ensure that the spring ice cover stayed intact into the summer. The extensive spring ice also preconditioned the ocean for ice formation in the late summer. The ice motion and atmospheric circulation patterns closely resembled those in another spring and summer when ice stayed intact in spite of there being no large icebergs. The primary findings of our study are:

- The springtime atmospheric circulation in the eastern and, in particular, central RS was highly anomalous resulting in southward ice drift and ice convergence during October 2002 and negligible ice motion during the rest of the spring.
- The widespread reduction of northward ice drift during November 2002 compared to other spring months, including near C-19, was mirrored in a lack of southerly winds at the time, and these winds and northward drift in the central RS were the weakest on record for the spring season.
- Prolonged ice formation in the western RS in the spring of 2002 due to unusually low air temperatures helped ensure that the ocean remained ice covered as C-19 moved rapidly north.
- Positive ice concentration anomalies only developed during the spring of 2002 and two other springs of extensive

ice, including one without a large iceberg, after widespread southward drift and ice convergence occurred.

- New ice formed very early in February 2003 because the ocean mixed layer was kept near the freezing point by the cold spring and by the extensive and compact spring ice cover reflecting much solar radiation in summer.
- Open water would have been very limited during the summer of 2003 even if C-19 had not occurred.
- The RS atmospheric circulation during the spring of 2002 and another spring with extensive ice but no large icebergs was fairly typical of El Niño events in general in which a statistically significant reduction in southerly winds occurs in the eastern RS.

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