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Atmospheric meridional circulation impacts on contrasting winter sea ice extent in two years in the Pacific sector of the Southern Ocean

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ABSTRACT

An explanation is sought for the marked variation in maximum sea ice extent observed between 2 years in the 2 areas of greatest interannual variability in winter ice extent in the South Pacific sector of the Southern Ocean. The rôle of ice recession in controlling ice extent is highlighted, and the adjustments in the near-surface atmospheric meridional circulation and air temperature that attend winter periods of ice retreat and advance are noted. Distinct meridional flow and air temperature adjustments attend periods of sea ice retreat that limit ice to higher than normal latitudes as well as ice advance to lower than normal latitudes. Ice advance leading to above-normal ice extent, for instance, takes place only when a lowering of air temperatures is accompanied by equatorward flow. A lack of warm air advection is, however, needed to adequately account for the development and maintenance of above-normal ice extent. Systematic meridional circulation changes also take place during the development and over the duration of ice extent anomalies. These are shown to emanate from adjustments of the semi-annual cycle in the extra-tropical South Pacific atmospheric circulation.

1. Introduction

Increasing evidence exists (Van Loon and Rogers, 1984; Van Loon et al., 1993; Hurrell and van Loon, 1994) that the semi-annual cycle (SAC), a climatological feature of the extra-tropical southern hemisphere atmospheric circulation, varies in magnitude not only on annual but also decadal time scales. In areas of the Southern Ocean where sea ice extent responds to atmospheric circulation variations, the possibility then arises that the SAC then modulates sea ice extent on these time scales. In this paper an hypothesis is tested that contrasting winter maximum ice extent anomalies observed during 2 years in the South Pacific occurred due to adjustments in the meridional, i.e., north-south, component of the atmospheric circulation in association with changes in the SAC.

According to Parkinson (1992), the maximum in South Pacific sea ice extent is reached in the late winter months of August and September and displays largest interannual variability in the eastern Ross Sea (RS) between 160 and 140°W and, to a lesser extent, the Bellingshausen Sea (BS) between 95 and 75°W (Fig. 1). Sea ice charts for these areas show that the maximum ice extent attained in a given year often reflects alterations in ice extent that occur within this coldest period of the year. These wintertime changes then lead to interannual amplitudinal adjustments of the dominant annual cycle in sea ice extent (Gloersen et al., 1992; Parkinson, 1992). Other climatological studies, e.g., for the Bering Sea (Walsh and Johnson, 1979; Niebauer, 1980; Overland and Pease, 1982; Niebauer and Day, 1989), show that winter ice extent variations are associated with both seasonal and shorter timescale atmospheric circulation adjustments. Over periods of a few

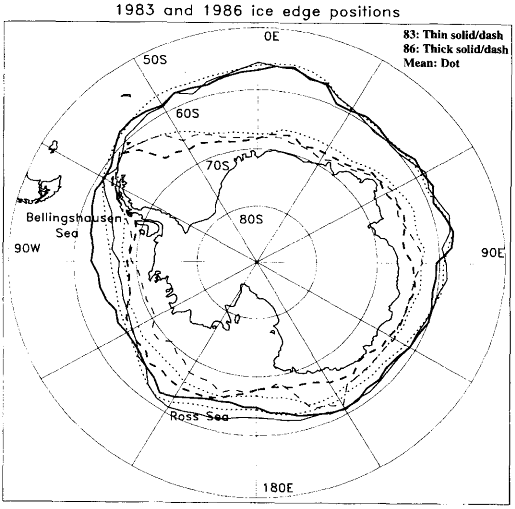

Fig. 1. Southern Ocean ice edge position (ice concentration >10%) in early May (broken lines) and mid-September (solid lines) in 1983 and 1986 plotted at 5° longitude intervals. Note that thickened lines (solid and dash) reflect the 1986 positions. Dotted lines indicate the mean positions of the ice edge in May and September. The study areas selected are the eastern Ross Sea (160–140°W) and the Bellingshausen Sea (95–75°W).

days, it is well-known that sea ice motion reflects changes in surface winds induced by synoptic weather systems (Muench and Ahlnas, 1976; Maslanik and Barry, 1989). At the same time establishment of winter sea ice anomalies, that may last several months, is also mirrored in systematic regional-scale circulation adjustments (Walsh and Johnson, 1979; Niebauer, 1980; Overland and Pease, 1982; Cavalieri and Parkinson, 1987; Niebauer and Day, 1989; Enomoto and Ohmura, 1990). These adjustments show up well in the meridional component of the atmospheric circulation (Niebauer, 1980) so that, for example, equatorward flows tend to accompany ice advance and become more dominant in winters of increased ice extent.

In 1983 and 1986, marked winter ice extent anomalies appeared in the two areas of highest winter interannual ice extent variability in the South Pacific, and these years have been selected to study the influence of meridional circulation changes on development of such anomalies. Gloersen et al. (1992) show winter maximum ice extent in the Bellingshausen-Amundsen Sea in 1983 was close to the lowest recorded in the 1978–1987 era, and was followed by a near-largest maximum in 1986. In the Ross Sea, anomalies of opposite sign occurred in the 2 years with a near-maximum ice extent in 1983. These anomalies stem from alterations in ice extent that occur from May onwards; in each area the ice edge position at the start of May in the winter of increased ice extent is at least as far poleward as that in the winter of reduced extent (Fig. 1). For this reason, only the 5-month period May–September is considered here and is referred to as winter. Attention in the paper is focused first on the contribution of various ice movement types to development of observed ice anomalies and identifying their associated meridional atmospheric circulation and air temperature characteristics. These are then related to seasonal or background changes in atmospheric circulation including the SAC, and the results obtained are used as a basis to explain the observed winter ice extent interannual variability. Prior to the analysis the quality of the ice data is considered.

2. Method

In this study, the weekly movement of the ice edge in the two years has been obtained from two different sources using distinct data and derivation methods. 1986 weekly ice edge (ice concentration >15%) positions were supplied by the Alfred Wegener Institute (AWI) and are based on daily ice concentration fields computed directly from the SMMR passive microwave data of the Nimbus-7 mission using the NASA team algorithm (Cavalieri et al., 1984). These daily fields are equivalent to those used to derive monthly average ice concentration for the Southern Ocean (SO) shown in Gloersen et al. (1992). In general, the calculated weekly average ice edge positions are based on 3 or 4 separate daily observations. Use was also made (see below) of AWI-processed sea ice edge data for 1987 and 1988 (based on Nimbus-7 SMMR data until August 1987 and SSM/I data from DMSP thereafter).

1983 ice edge position (ice concentration >10%) data have been obtained from digitized weekly operational sea ice concentration charts produced by the US Navy/NOAA Joint Ice Center (JIC) (now the National Ice Center) and made available by NSIDC in Boulder. These charts are manually drawn and based on data from various satellite sensors, e.g., passive microwave and AVHRR, of differing spatial resolution. Owing to the use of averaging methods in the case of AWI ice edge data, and the emphasis on general rather than detailed changes in the ice edge position in the case of the manually derived charts, however, both could be expected to yield similar weekly ice edge positions. The influence of perturbations of the ice edge that migrate eastward at daily rates of up to 130 km in response to the passage of extra-tropical cyclones (Cahalan and Chiu, 1986) on the calculated AWI weekly ice edge positions ought to be minimised by the averaging method used here.

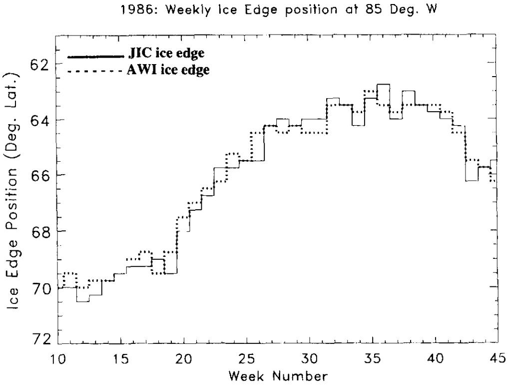

Fig. 2. Trace of weekly ice edge movement (° latitude) from the start of winter to the start of spring in 1986 at 85°W. The JIC position is shown by the solid line and the AWI position by a dotted line. The week number refers to the number of weeks from the start of 1986.

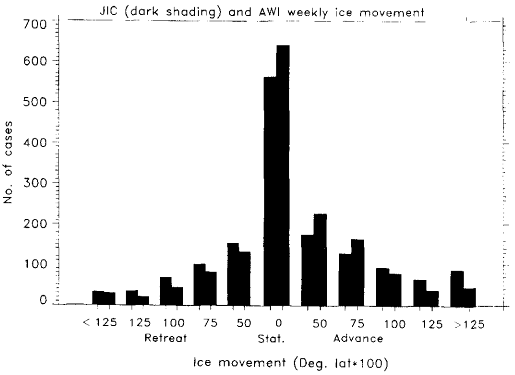

Fig. 3. Distribution (frequency expressed as percentage) of weekly ice edge movement derived from JIC (left bar) and AWI (right bar) ice edge data for the South Pacific region of the Southern Ocean (160–75°W) for the winter (May–September) period in the years 1986–88 ($n = 1495$). Note that the interval of the movement classes is 0.25° latitude between 0.5° and 1.0° latitude and that movement shown as '0' refers to movement of 0.25° latitude or less.

Weekly ice edge movement for the two years has been worked out by taking the ice edge position in a given week and subtracting the corresponding position in the previous week from it. This movement was then classified using a simple three-way scheme in which equatorward movement is categorised as advance and poleward movement as retreat when the movement is 0.5° latitude or more. The ice edge was taken as stationary in remaining cases. Weekly ice movement, as determined from the 1986–88 AWI data set, of 0.5° latitude or more accounts for more than 70% of total South Pacific (160–75°W) winter ice advance and retreat.

The JIC and AWI winter weekly ice edge data have been compared for the extended 1986–88 period. Inspection of the data (Fig. 2) reveals the timing and magnitude of maximum winter ice extent is comparable in each. Also, no bias in ice edge position towards higher or lower latitudes is apparent but discrepancies in ice edge position do appear in individual weeks, e.g., week 26 in Fig. 2, that result in differences in week-to-week movement, e.g., weeks 23–24 and 25–27. In the latter period, JIC advance lags that in the AWI set and this is a common problem. In addition, more than 90% of all weekly latitudinal movement from both centres does not exceed 1° latitude (Fig. 3) but movement not exceeding 0.25° latitude accounts for 38% of the JIC data compared to 43% in the AWI series. With inclusion of advance of up to 0.75° latitude, these values rise to 58 and 69% respectively. The reduced frequency of occurrence of small ice movement in the JIC series is compensated by a higher frequency of larger movement; cases of advance of 1° latitude or more comprise 16% of the JIC set compared to 11% in the AWI set (246 against 162), and cases of ice advance >1° latitude in the JIC set are close to double the AWI figure (153 against 83). This is consistent with the more step-like nature of advance in the JIC dataset that shows up in time series plots, e.g., weeks 26–27 in Fig. 2. Also, instances of retreat of

0.5–1° latitude are distinctly more prevalent in the JIC dataset (320 against 255).

A breakdown of AWI weekly movement according to ice movement in the JIC data set based on the 3-way classification (Fig. 4) indicates the majority of JIC weeks with a stationary or advancing ice edge are reproduced in the AWI series. Discrepancies such as AWI ice advance with a stationary JIC ice edge and vice-versa are however also seen, e.g., 162 out of the 562 JIC stationary cases appear as advance in the AWI case. Discrepancies also appear in the breakdown of JIC retreat cases; only 158 of the 386 JIC cases appear in the AWI series and 169 are stationary. Such problems with the JIC data, including incorrect representation of the direction of ice movement, are consistent with Kniskern (1991) who notes the accuracy of the JIC ice edge position at a given place and time in the SO can sometimes fall to 100 km. He attributes this to cloud cover that prevents accurate delimitation of the ice edge in AVHRR visible and infra-red imagery used by JIC.

Due to the lack of AWI data for 1983, a method was devised to overcome some of the JIC problems and, in particular, the lack of updating when applying the weekly classification. In the correction method weeks of stationary ice movement (<0.5° latitude) were changed to advance if advance of 1° latitude or more occurred in the following week. Instances of retreat of at least 0.5° and <1° latitude were reclassed as stationary if followed by advance of 1° latitude or more. Finally, cases of ice advance of <1° latitude were designated stationary if followed by retreat of 1° latitude or more. This scheme helps resolve problems such as lack of updating in week 26 in Fig. 2, and 16% of the 1983 weekly JIC ice movement cases were reassigned in this way. Possible outstanding difficulties with the adjusted 1983 data

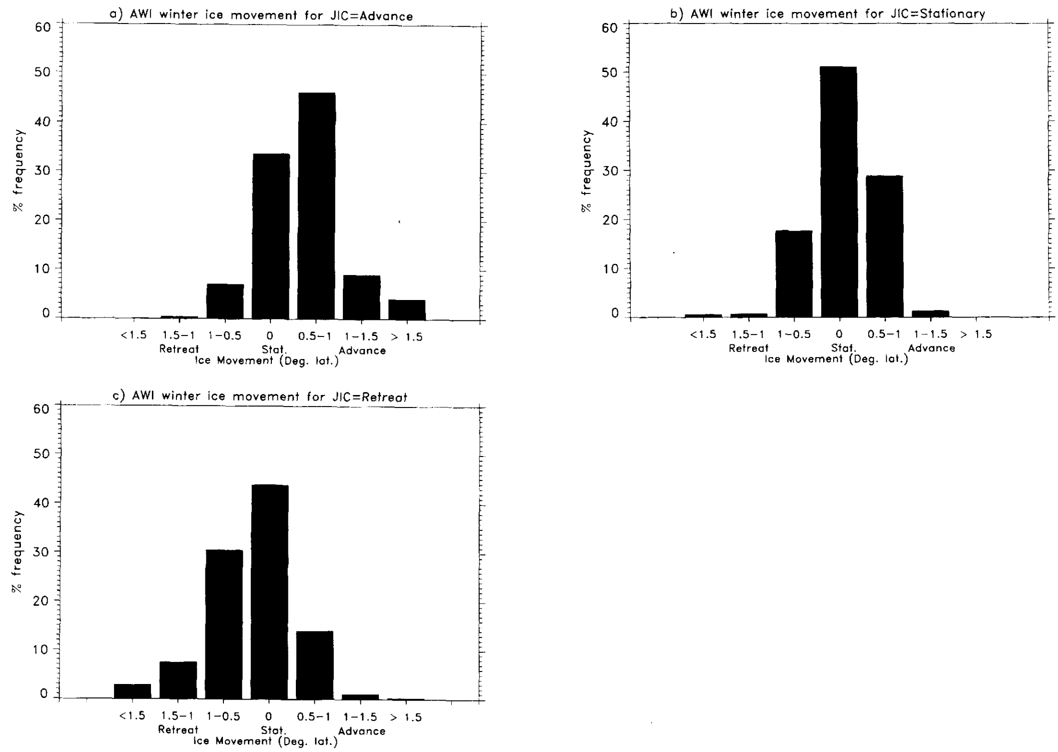

Fig. 4. The distribution of AWI weekly ice edge movement shown according to whether the JIC ice edge (a) advances, (b) remains stationary or (c) retreats in the winter months May–September in the period 1986–88 for the South Pacific region of the Southern Ocean, $n = 1495$.

are noted below. In both study areas actual weekly ice edge movement was calculated and classified at 5 points spaced at 5° longitude intervals. For a given measurement point this yields 22 cases of weekly movement in the winter period, i.e., a total of 110 cases (22 weeks*5 measurement points) for each study area. The winter area-average number of weeks of advance, retreat etc., referred to henceforth was derived by dividing the total number of cases in each ice movement class by 5.

Daily meridional (north-south) geostrophic wind and air temperature data for 1983 and 1986 have been drawn from the set of numerical analyses routinely produced by the Australian Bureau of Meteorology since 1972. For the South Pacific marginal ice zone (MIZ) these data are available for the 1000 mb, i.e., near surface, standard pressure level at 65 and 60°S and at the same 5° longitude intervals as the ice edge position data. These numerical analysis data have been used to construct weekly averages that correspond to weeks in the ice movement record. The analyses have been widely used in studies of southern hemisphere meteorology. They include all available surface and upper-air observations along with tropospheric temperature retrievals from satellite data (since 1976). Karoly and Oort (1987) indicate the wind fields, including their daily variability in winter (June–August), are well represented in the lower troposphere. In contrast, they suggest that lower tropospheric air temperatures (850 mb) are too warm in the South Pacific and that the model underrespresents the winter variability. Scrutiny of their Fig. 4, however, shows that the lower tropospheric (850 mb) winter (June–August) temperatures for the period 1972–82 in the BS region are only 1°C warmer than in fields generated from a dynamical model that includes all southern hemisphere radiosonde data for the period 1963–73. In the RS area centred on 150°W, 60°S the warm bias is 2°C. Owing to the different epochs used in this comparison differences of this magnitude might be expected to arise from real decadal variability noted by van Loon et al. (1993).

In general, the Australian daily and seasonal fields are considered (Van Loon, 1980) to well depict the distribution of cyclonic and anticyclonic centres but it should be noted that uncertainty continues at present over their actual intensity due to paucity of observations over the oceans. As a result, circulation features may be more intense than indicated. It follows that, contrary to Karoly and Oort (1987), daily variability is possibly conservative in the case of wind strength as well as air temperature in the Australian analyses. As in previous studies for the South Pacific and SO in general (Van Loon and Rogers, 1984; Fitch and Carleton, 1991; Van Loon et al., 1993; Hurrell and Van Loon, 1994), it is shown later that these conservative data do yield statistically robust and consistent results for the widely-separated RS and BS.

3. Evolution of ice extent anomalies

In both study areas, weeks of ice advance and retreat individually occupy only a fraction of the winter season. In the BS, for example, advance occupies 7.8 out of a possible 22 weeks in the 1986 winter, the case of above-normal ice extent, and 10.8 in 1983 (Table 1). This compares with 1.6 retreat weeks in 1986 and 4.8 in 1983. In the BS changes in the frequency of retreat between the two years are compensated by changes in the frequency of weeks with a stationary ice edge, the latter decreasing by half between 1986 and 1983. In the RS changes in the incidence of retreat mainly occur at the expense of ice advance. Overall, weeks with a stationary or advancing ice edge dominate winters of above-normal winter extent, e.g., 20.4 out of a possible 22 weeks in 1986 against 17.2 in 1983 in the BS. The area-averaged total amount of ice advance (irrespective of magni-

Table 1. *Area-averaged frequency of weeks when the ice edge advances, remains stationary or retreats in the May–September period in 1983 and 1986 in the Bellingshausen (BS) and Ross (RS) Sea study areas*

Area/ice movement type	1986	1983
BS advance	7.8	10.8
BS stationary	12.6	6.4
BS retreat	1.6	4.8
RS advance	7.0	11.0
RS stationary	9.0	7.4
RS retreat	6.0	3.6

See text for definition of ice movement types. The May–September period consists of a total of 22 weeks in both years.

tude) shown in Table 2 is comparable in winters of contrasting ice extent in the two areas but this is not true of ice retreat, e.g., in the BS total advance decreases by 2.5% in the 1983 winter, the case of below-normal extent, compared to 1986 but retreat increases by 117%. In the RS retreat increases by 67.5% between the same ice states.

Noting that ice movement of 0.5° latitude or more accounts for most winter ice advance and retreat, it is clear that the bulk of ice movement leading to contrasting winter ice extent anomalies in the two regions takes place quickly. As expected, winter ice retreat is less frequent and of lower magnitude than advance but anomalies in both study areas are in fact driven by ice retreat. As a result, the incidence of a stationary or retreating ice edge between periods of advance determines ice extent rather than ice advance alone. In other words extension of sea ice to anomalously low latitudes depends on a combination of ice advance and *lack of retreat.* Independent studies for the Bering Sea (Niebauer, 1980; Cavalieri and Parkinson, 1987) bear out the impact of winter (October to March) ice retreat on maximum ice extent. Neibauer (1980) shows that retreat, defined as periods with a minimum reduction in the total ocean area occupied by sea ice of 5%, is least frequent at times of greatest ice extent and vice-versa (see his Fig. 6 and Table 3). The impact of ice recession on winter maximum ice extent in the Amundsen–Bellingshausen Sea area in another year has also been noted by Ackley (1981).

Table 2. *May–September area-averaged total ice advance and retreat (° latitude) and difference from May to September in 1983 and 1986 in the Bellingshausen (BS) and Ross (RS) Sea study areas*

Area	Year	Advance	Retreat	Diff.
BS	1986	8.0	2.4	5.6
	1983	7.8	5.2	2.6
RS	1986	8.7	6.7	2.0
	1983	9.0	4.0	5.0

A positive difference indicates that the ice edge position at the end of September is *equatorward* of that at the beginning of May, i.e. an overall expansion of the ice pack occurs in the five months. Note that ice advance and retreat refers to all weekly ice advance and retreat irrespective of the actual amount of movement. A separate 3-way classification of ice movement used to investigate ice-meridional circulation interactions is described in the text.

4. Meridional circulation and air temperature behaviour

4.1. *Air temperature*

In the BS, the average 1000 mb air temperature at 65°S, the approximate northern limit of sea ice is −3.7°C during ice advance in the 1983 winter of decreased ice extent (Table 3a). The equivalent value for 1986 is −6.4°C and weekly average air temperatures toward the edge of the pack in this case exceed −3.0°C in just 13% of such cases (Fig. 5a). A comparable average temperature obtains in weeks with a stationary ice edge in 1986 when temperatures remain below −3°C in 89% of cases. During retreat in the 1983 winter of reduced ice extent the average temperature compares with ice advance at the time. This result may stem from updating problems in the JIC data as retreat cases associated with temperatures below −5°C are confined to two weeks in the 1983 winter. Temperatures in the preceding weeks, however, are between −1.6 and −2.8°C. Omission of these problematic cases yields an average temperature of −2.3°C for retreat in 1983.

In the RS (Fig. 5b and Table 3a), where temperature behaviour in the ice movement categories mostly mimics that in the BS, the average temperature near the ice edge is −1.8°C for retreat in the 1986 winter of reduced ice extent (when AWI data is used). Weekly average air temperatures range from +1.9 to −3.3°C in 22 of the 30 retreat cases. These values are conservative as the RS ice edge in 1986 lay up to 2° latitude north of the air temperature measurement points from July onwards. The non-parametric χ^2 test has been used to test the null hypothesis that the observed frequencies (in predetermined classes) of weekly average air temperatures in the ice movement types (Table 3a) that effect ice anomalies do not differ from the expected frequencies (taking the overall winter population for 1983 and 1986). The null hypothesis can be rejected at at least the 1% level in all but one of the relevant ice movement types in both study areas. The exception is stationary ice edge cases in the BS in 1986 for which the null hypothesis can be rejected at the 5% level only. Over the winter season as a whole the RS

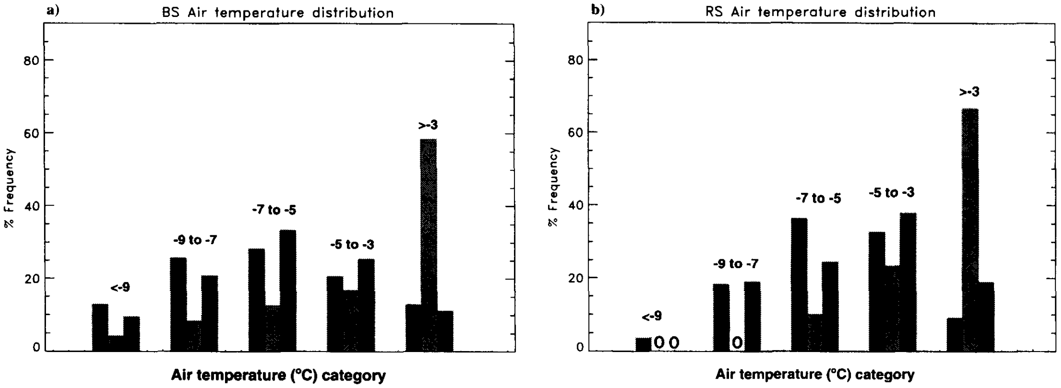

Fig. 5. The distribution (expressed as percent frequency) of air temperature (°C) in the vicinity of the marginal ice zone at 65°S shown in 5 specified ranges (indicated on the tops of the 5 groups of bars) for 3 types of weekly ice movement that influence sea ice extent anomalies (see text): advance in winters of above-normal ice extent (left bar), a stationary ice edge in the same winters (right bar) and retreat in winters of below-normal ice extent (middle bar) for (a) the BS and (b) RS. Zeros indicate zero %.

total number of cases not reaching −3°C, a level where melting could be expected (Zwally et al., 1983) is 56 in 1986 and 88 in 1983 (of the total 110). The BS figures are 63 in 1983 and 98 in 1986.

It is evident that ice movement types that promote above- and below-normal ice extent are associated with systematic air temperature adjustments in proximity to the MIZ, e.g., the 4°C air temperature difference in the BS between ice advance, leading to above-normal winter ice extent, and ice retreat, leading to below-normal extent (after exclusion of the apparently problematic ice retreat cases for 1983). Importantly, excluding the problematic 1983 JIC data, the average temperature adjustments in these two movement categories in the BS and RS conform to the Zwally et al. (1983) finding that SO sea ice does not persist when the surface air temperature exceeds −2°C.

An unexpected finding is that air temperatures in weeks with a stationary ice edge in winters of increased ice extent are depressed almost as much as during ice advance. The implication is that air temperature behaviour on its own does not explain ice advance to anomalously low latitudes. Since explanations of increased ice extent need to take into account the preference for retention of sea ice, i.e., lack of retreat, between periods of advance, however, it is also clear that suitable thermodynamic conditions for this to happen do prevail.

Independent support for a general lowering of air temperature favouring retention of above-normal winter sea ice extent is provided by Allison (1989) drawing on surface air temperature data from drifting buoys in the MIZ in the Indian Ocean sector of the SO. During onset of above-normal winter ice extent his Fig. 2b indicates air temperatures in the zone rise to between −2 and 0°C on only a handful of days in a 40-day period but fall as low as −8°C at other times. A period of 10 days follows when the temperature remains around 0°C but limited melting at this time is followed by further development of the positive ice extent anomaly thereafter (his Fig. 1). By contrast, in the Bering Sea Niebauer (1983) finds a rise of surface air temperature above −2°C (his Table 3) in most periods of winter ice retreat. Thermodynamic conditions suited both to development and retention of above-normal ice extent thus do appear to exist in the BS and RS in the 2 years.

4.2. *Meridional atmospheric circulation*

In winters of increased ice extent in the RS and BS equatorward flows appear on average in weeks with an advancing ice edge and in 85 to 93% of individual cases (Table 3b and Fig. 6a, b). In the opposite ice state poleward flows dominate weeks of ice retreat, e.g., 96% of cases in the BS in 1983 and all of them when omitting cases from the two weeks with problematic ice data. In both areas

Table 3. *(a) Air temperature (°C) characteristics for contrasting ice movement types in the BS and RS: n, the number of cases when the ice advances, retreats or is stationary, Avg, the average temperature, SD, the standard deviation, T> −3°C, the frequency of cases with temperatures above this threshold and extrema; (b) meridional flow (m s^{-1})* with n *as above, Avg, the average meridional flow, SD, the standard deviation, +V%, percentage of cases with equatorward flow, and Extrema for the same areas*

(a) Temperature (°C)
BS

Ice movement	*n*	Avg	SD	*T* > −3°C	Extrema
1986 adv.	39	$\underline{\underline{-6.4}}$	2.9	5	−1.4/−14.4
1986 stat.	63	$\underline{-6.0}$	2.3	7	−0.6/−14
1986 ret.	8	−6.0	2.0	0	−3.5/−9.7
1983 adv.	54	−3.7	2.0	20	0.4/−8.9
1983 stat.	32	−4.0	2.4	13	0.2/−8.7
1983 ret.	24	$\underline{\underline{-3.6}}$	2.5	14	−0.6/−9.1

RS

Ice movement	*n*	Avg.	SD	*T* > −3°	Extrema
1986 adv.	35	−5.5	2.6	8	−0.8/−10.5
1986 stat.	45	−3.1	2.3	26	1.9/−7.7
1986 ret.	30	$\underline{\underline{-1.8}}$	2.3	20	1.9/−6.2
1983 adv.	55	$\underline{\underline{-5.5}}$	2.0	5	−1.7/−9.1
1983 stat.	37	−5.9	2.2	7	0.9/−8.8
1983 ret.	18	−3.3	2.5	10	0.4/−8.1

(b) Meridional wind (m s^{-1})
BS

Ice movement	*n*	Avg.	+*V*%	SD	Extrema
1986 adv.	39	$\underline{\underline{+4.3}}$	85	3.9	+10.3/−6.2
1986 stat.	63	+0.9	52	5.1	+9.9/−7.9
1986 ret.	8	−1.4	38	4.0	+3.6/−6.3
1983 adv.	54	−2.3	31	3.5	+5.1/−9.2
1983 stat.	32	−3.3	19	4.5	+4.9/−13.2
1983 ret.	24	$\underline{\underline{-6.6}}$	4	2.9	−3.5/−12.5

RS

Ice movement	*n*	Avg.	+*V*%	SD	Extrema
1986 adv.	35	+2.5	71	4.1	+10.6/−4.7
1986 stat.	45	−2.6	22	3.2	+5/−9.2
1986 ret.	30	$\underline{\underline{-6.2}}$	10	4.8	+4.2/−14.8
1983 adv.	55	$\underline{\underline{+2.6}}$	93	1.8	+5.8/−2.6
1983 stat.	37	+1.2	81	1.4	+4/−1.3
1983 ret.	18	+0.8	56	2.1	+5.1/−3.1

All data are for 65°S in the vicinity of the MIZ. Equatorward flow is denoted by positive values in the second column. Temperature and flow adjustments that are statistically significant with ice advance or a stationary ice edge during above-normal ice extent in the BS in 1986, advance in the RS in 1983 and with retreat giving below-normal extent in the BS in 1983 and RS in 1986 (see text) are underlined (<5%) or double underlined (<1% level).

flows at these times of advance and retreat are statistically different from the overall population at <1% level (χ^2 test). In the BS mixed flow behaviour, that is not statistically significant, appears in stationary weeks in 1986 giving an average equatorward flow of 0.9 m s^{-1}. This is 3.4 m s^{-1} less than advance at this time. Mixed flow directions typify remaining ice movement categories in the different ice extent states.

Despite a striking reversal in the meridional flow direction between weeks of ice advance in winters of increased ice extent and retreat with reduced extent, simple meridional circulation–ice movement associations are clearly absent. Further inspection of the data, however, reveals the ice movement categories responsible for ice extent anomalies can be distinguished from other movement cases by taking into account both the flow direction and air temperature (Table 4); only weeks of ice advance to anomalously low latitudes are attended by a combined lowering of temperature and prevalent equatorward flow, and only retreat to anomalously high latitudes is associated with a general raising of air temperature and consistent poleward flows.

Warm air advection with poleward flows has been independently found during a 2-week period of significant winter ice retreat in the BS (Ackley and Keliher, 1976). Poleward flows also generally occur with surface temperatures above the Zwally et al. (1983) threshold during winter ice retreats (lasting up to several weeks) in the Bering Sea (see Table 3 in Neibauer, 1980). The impact of a lack of warm air advection on ice behaviour in the RS and BS is also indirectly indicated by the fact that air temperatures in periods of ice advance in winters of reduced ice extent fail to reach those that occur during retreat despite the presence of poleward flows. It is thus deduced that ice movement leading to contrasting winter ice states in the BS and RS does arise from meridional circulation adjustments but only when these are attended by appropriate warm or cold air advection.

Recalling that thermodynamic conditions in weeks with a stationary ice edge in the BS in 1986 are indistinguishable from those in advance at the time, a similar problem does not arise with the meridional circulation; only advance is dominated by equatorward flow and the average meridional component in the stationary category is close to zero. This implies that advance in winters

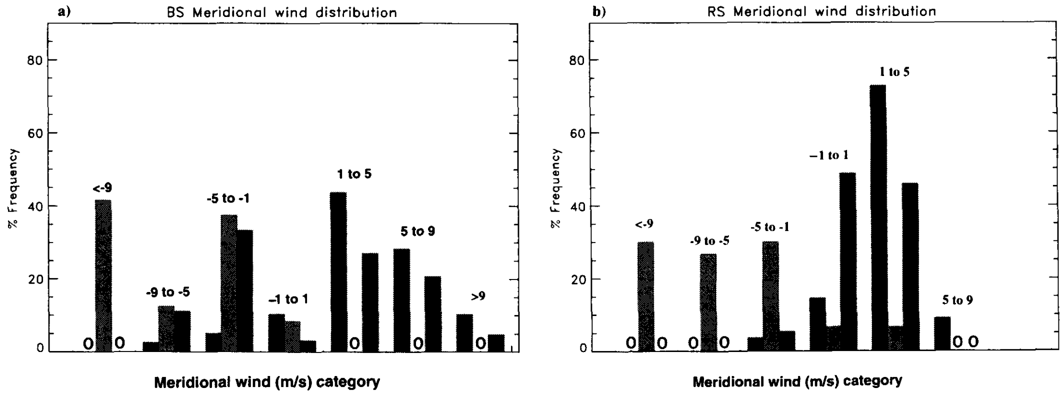

Fig. 6. The distribution (expressed as percent frequency) of the meridional wind component (m/s) in the vicinity of the marginal ice zone at 65°S in 7 specified ranges (indicated on the tops of the 7 groups of bars) for 3 types of weekly ice movement that influence sea ice extent anomalies (see text): advance in winters of above-normal ice extent (leftmost bar), a stationary ice edge in the same winters (right bar) and retreat in winters of below-normal ice extent (middle bar) for (a) the BS and (b) RS. Ranges with positive values denote equatorward flows. Zeros indicate zero counts.

Table 4. *Summary of the air temperature and meridional flow adjustments associated with ice movement categories inducing above- and below-normal ice extent in the South Pacific study areas*

Ice behaviour	Temperature adjustment	Merid. flow direction
advance to low latitudes	cold	equatorward
stationary at low latitudes	cold	mixed
retreat to high latitudes	warm	poleward

of increased ice extent is primarily due to strengthened equatorward flow. The influence of the meridional wind in facilitating expansion of the MIZ is consistent with findings of a sea ice modelling study (Stossel et al., 1990) that includes the South Pacific area of the SO; the model yields sufficiently extensive winter ice only after inclusion of surface winds that advect ice to lower latitudes. In addition, using observational evidence, Allison (1989) also directly ascribes above-normal ice extent in the Indian Ocean region in one winter to ice motion. He shows that a buoy trapped in the MIZ continuously drifted equatorward as sea ice extended further into the ocean. Ice advection also promotes expansion of winter sea ice in the Bering Sea (Muench and Ahlnas, 1976) and off Labrador (Prinsenberg and Peterson, 1992).

4.3. Persistence of equatorward flows

The increased incidence of equatorward flows in winters of increased ice extent appears to indicate that the noted general reduction in air temperature at such times may be due to general or background changes in the meridional circulation. In the Bering Sea region such adjustments are well represented by alterations in equatorward flow persistence (Neibauer, 1980). To test this idea the available daily time series of 1000 mb meridional wind component values have been low-pass filtered to retain frequencies <0.2 cpd. Instances of 5 days or more of continuous equatorward flow in the filtered series were taken to indicate periods of persistent flow (ignoring reversals to a poleward flow on individual days). In the BS such flows occupy nearly half of all winter days in 1986 (Fig. 7) against 16% in 1983. Two periods of persistent equatorward flow of 54 days in total span the period from June to the first week of August in 1986 when ice retreat is confined to a single week between 80 and 75°W. In the RS days of persistent flow vary from 62% in the 1983 winter to 23% in 1986. A lack of persistent equatorward flow in the BS in another winter of

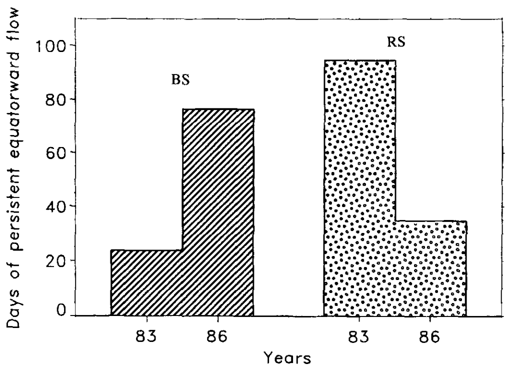

Fig. 7. The frequency (days) of persistent equatorward flow (see text) in the BS (hatched shading) and RS (stippled) for the May–September period (a total of 153 days) in 1983 and 1986.

below-normal ice extent in the Bellingshausen-Amundsen Sea area is indicated in Fig. 2b of Jacobs and Comiso (1993). Changes in meridional flow direction in individual weeks of retreat and advance leading to contrasting ice extent are thus mimicked by systematic alterations on seasonal time scales. This result concurs with the Neibauer (1980) finding for the Bering Sea that a persistent equatorward flow regime is a hallmark of winters of anomalously extensive sea ice. It also helps explain why air temperatures remain suppressed outside periods of ice advance allowing positive ice extent anomalies to stay intact.

5. The influence of the semi-annual cycle

In the climatological mean, the annual cycle of sea level pressure in the extra-tropical South Pacific is dominated by a semi-annual wave (Hurrell and Van Loon, 1994). Compared to the annual average, the zonally averaged circulation at 70°S is anomalously anticyclonic, implying anomalous equatorward flow, in the 3 winter months centred on June, and anomalously cyclonic, implying anomalous poleward flow, in the transitional seasons centred on March and October. The implied climatological meridional flow behaviour is well represented in the two study areas only in winters of increased ice extent, e.g., in the BS in 1986 (Fig. 8a) with an average equatorward flow from May to August reversing to a poleward flow from February to March and September to October. Opposite seasonal flow adjustments appear in years of low winter ice extent, e.g., the BS in 1983, when poleward flows predominate in winter (Fig. 8b). Relative changes in the meridional flow between years of contrasting winter ice extent in the BS (Fig. 8c) and RS (not shown) are also consistent with changes in modulation of the flow by the SAC. Clearly, therefore, general changes in meridional circulation, seen in alterations in persistent equatorward flow, between the winters of contrasting ice extent studied here are symptomatic of adjustments in the annual cycle, i.e., above-normal maximum winter ice extent is associated with an increase in the amplitude of the SAC in the meridional flow and vice-versa.

Present results indicate that modulation of the lower tropospheric meridional flow by the SAC in a given year varies between different regions and that this spatial variation can induce contrasting regional winter ice extent anomalies. Contrasting regional ice extent anomalies are in fact a well known feature in the SO (Gloersen et al., 1992). Support for the regionally-varying modulation of flows by the SAC between the RS and BS in 1983 is provided by Enomoto and Ohmura (1990). Using ECMWF analyses they show (their Fig. 10) that the monthly average position of the surface circumpolar trough, known to be locationally modulated by the SAC (Van Loon et al., 1993), systematically moves equatorward in the RS from April to July, as sea ice extent in this area increases, and poleward from August to November, both as expected from climatology. By contrast, in the BS the trough remains almost stationary on average at about 68–69°S from March to December. This suggests the trough is in fact located on the poleward side of the ice edge (Fig. 1) throughout the 1983 winter. Temperate cyclonic activity peaks in the vicinity of the circumpolar trough (Jones and Simmonds, 1993), and the observed poleward displacement of the trough in the BS implies a greater prevalence of warm air advection here than in the RS that concurs with present results. As the circumpolar trough locates further poleward winter sea ice extent in the South Pacific thus appears to diminish. From these results and independent findings it is thus deduced that the SAC did bring about contrasting winter sea ice anomalies in the RS and BS in the two years studied. The differing

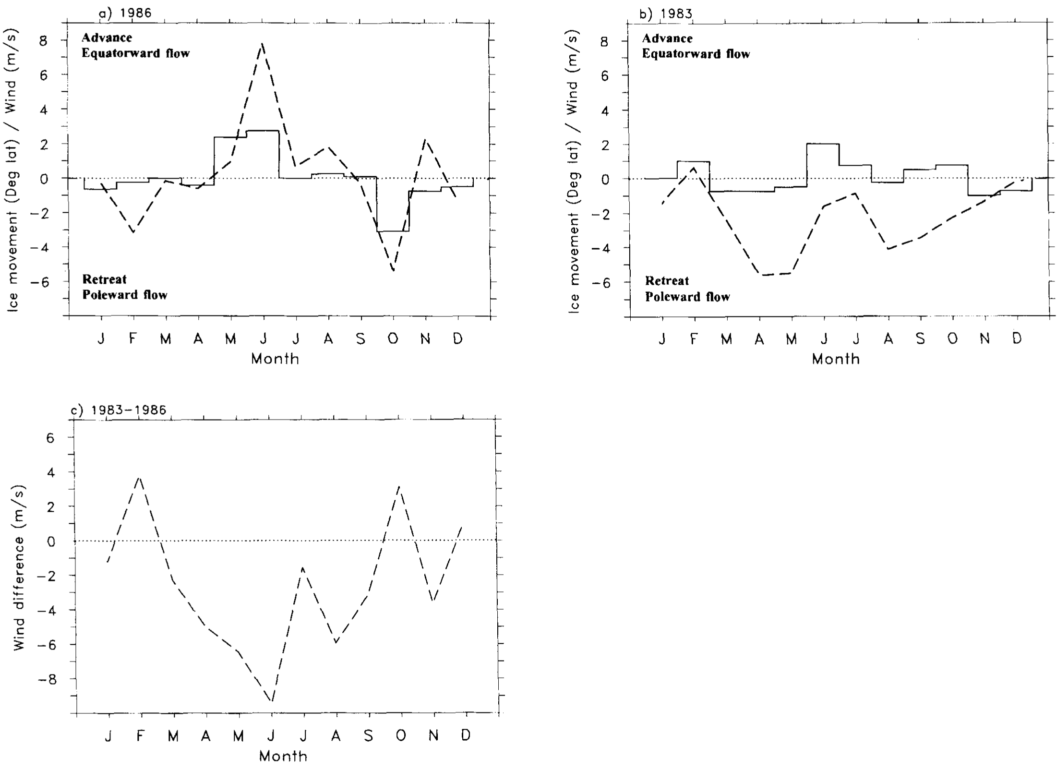

Fig. 8. Monthly movement of the ice edge (° latitude) in the Bellingshausen Sea at 90°W (open bars) and the corresponding monthly average 1000 mb meridional wind component (m s^{-1}) at 65°S, 90°W (dashed line) in (a) 1986 and (b) 1983, and (c) the difference in the monthly average meridional wind (1983–1986). Comparable changes take place in other parts of the region. Positive values in (a) and (b) denote equatorward ice movement and a monthly average equatorward flow, and in (c) an anomalous equatorward flow. Note that the ice edge position in the region at the beginning of May is comparable in the two years but that the overall equatorward ice movement from May–September period is greatest in 1986.

meridional circulation behaviour between the two regions in both years points to large-scale circulation changes in the southern hemisphere ultimately driving regional sea ice extent anomalies.

6. Conclusions

Interannual variations in winter sea ice extent anomalies in the South Pacific are associated with distinct alterations in the meridional lower tropospheric circulation present on both weekly and seasonal time scales. On the short time scale directionally opposing meridional flows frequent periods of ice advance, leading to above-normal winter extent and ice retreat, leading to below-normal ice extent. Recourse had to made to the existence of warm or cold air advection, however, to distinguish those ice movement types that promote anomalous winter ice extent states from ice movement at other times. A consistent combination of equatorward flow and a lowering of temperature in the vicinity of the MIZ, for example, is limited to ice advance to anomalously low latitudes. One of the most important findings of this study was that contrasting ice extent anomalies do not depend solely on ice advance or the lack of it. The appearance of retreat between periods of ice advance also needs to be taken into account and understood. Reduced winter ice retreat in winters of above-normal ice extent is most closely related to a lack of warm thermal advection.

On seasonal time scales, persistent equatorward flows are a feature of the meridional circulation only in years of above-normal ice extent. With their attendant cold air advection such flows help to suppress temperatures outside periods of ice advance that then precludes removal of positive ice extent anomalies. In turn, this contrasting meridional circulation behaviour is shaped by the semi-annual cycle; modulation of the flow by this cycle strengthens as winter sea ice extent increases and vice-versa. Spatial variations in the modulation of the meridional flow by a semi-annual cycle were invoked to explain the simultaneous appearance of contrasting winter ice extent anomalies seen in the RS and BS in the two years. The latter finding is consistent with the idea that hemispheric atmospheric circulation changes drive winter sea ice extent anomalies in the South Pacific sector of the Southern Ocean.

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