Ice-ocean-atmosphere interactions at high southern latitudes in winter from satellite observation*

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A satellite-derived index of cyclonic activity is used to evaluate the relationship between the middle and higher latitude atmospheric circulation and the Antarctic sea ice regime in winter. The mean month-to-month variations in the latitude band of maximum depression frequency reflect the semi-annual oscillation of surface pressures, and show little dependence on the seasonal expansion of the pack ice zone. However, marked interannual variations in cyclonic activity reveal close ice-ocean-atmosphere feedbacks operating at the synoptic scale for certain high latitude regions. Increases between winters in the frequencies of cyclones entering the circumpolar trough serve to promote ice advances in some longitudes, mainly through enhancement of ice advection processes, while retarding expansion in other sectors. Important surface-atmosphere feedbacks are evident for ice-extent variations in the Weddell Sea sector, as given by the frequencies of cyclones occurring at the ice edge. The interannual variation in the position of the ice margin for the South Pacific influences the dominant latitude zone for cyclogenesis. Similarly, a large open-water polynya in the Weddell Sea is found to increase substantially the incidence of high-latitude cyclogenesis for those winters in which it is present. It is implied that the occurrence and persistence of such areas of low ice concentration are crucial for estimates of the total energy budget within the seasonal sea ice zone and the possibly marked effects of interannual variations in ice extent and concentration upon those estimates.

Introduction

Considerable interest is currently being focused on the importance of interannual variations in surface characteristics for the generation or augmentation of climatic anomalies (e.g. Henderson-Sellers 1980). This is particularly critical in the snow and ice-covered higher latitudes of both hemispheres (between about 60–70°), which constitute the zones of greatest seasonal range in surface albedo (Kukla and Robinson 1980). Circulation teleconnections have been found to occur between these regions and middle to low latitudes (Goody 1980). A highly significant modifier of the oceanic and atmospheric energy budgets of the southern oceans is the seasonal variation in areal extent of the Antarctic sea ice, which is of the order of 18 x 10⁶ km², and the timing of its maximum and minimum extent (Polar Group 1980; Gordon and Taylor 1975; Weller 1980; Budd 1981). While interannual variability of the total ice-covered area is apparently small (Zwally, Parkinson, Carsey, Gloersen, Campbell and Ramseier 1979a, b), large year-to-year variations occur in the timing and rate of ice advance and retreat (Budd 1975), particularly at the regional level (Budd 1975). These longitudinal asymmetries are related closely to variations in the atmospherically and oceanically-linked processes of ice accumulation, ablation, deformation, and drift (Ackley 1979; Lemke, Trinkl and Hasselmann

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1980). Thus, an increase in the regional ice extent in one year is approximately balanced by a decrease in another sector. The interaction of the atmosphere with the Antarctic pack, operating via non-linear feedbacks, is highly complex and takes the form of a wide range of synoptic responses (Radok, Streten and Weller 1975; Ackley 1981). Several studies have claimed effects of the atmosphere on the regional ice regime (e.g. Ackley 1979). Others have demonstrated an apparent forcing exerted by the pack ice on the intensity of the zonal westerlies (Streten 1973; Streten and Pike 1980), a relationship reproduced in numerical modelling experiments (Simmonds 1981), and on the seasonal variations in the frequency of cyclones in different latitude belts (Schwerdtfeger and Kachelhoffer 1973). However, fewer studies document the interactive feedback occurring between a given sea ice regime and the synoptic-scale atmospheric circulation on the interannual time scale (e.g. Ackley and Kelihf 1976). Investigation of sea ice-atmosphere interactions in the Antarctic is currently an important component of the Australian climatic research effort (Streten 1980a).

Acquisition of satellite data for the southern hemisphere oceans continues to be of major importance in routine weather analysis and forecasting (Noar 1979), as well as for studying the essential characteristics of the general circulation (e.g. Streten and Troup 1973; Streten 1975; Yasunari 1977; Carleton 1979a). Recently, augmentation of the satellite product by data from drifting buoys has shown promise for more detailed climatological investigations (Guymer and Le Marshall 1981). Similarly satellite data, particularly those in the microwave range, are essential to the operational surveillance of Antarctic sea ice extent and concentrations (Zwally, Wilheit, Gloersen and Mueller 1976), and for the derivation of research-oriented data products (Godin 1979). A recent study (Streten and Pike 1980) utilises these data in an investigation of the relationship between the seasonal regime of the Antarctic sea ice and certain synoptic indices of the higher latitude atmospheric circulation. The present paper examines the problem of ice-ocean-atmosphere interactions on the interannual time scale using a satellite-derived cloud vortex inventory as a single index of the wintertime atmospheric circulation over the southern oceans. Emphasis is placed on the mutual forcing evident between the ice and the atmosphere in certain key regions, and on the climatic influence of low ice concentration/open-water areas within the winter pack. The latter are of major significance for estimates of the seasonal energy budget regimes of the South Polar region (e.g. Weller 1980).

Winter mean cyclonic activity and surface-atmosphere interactions

Analysis of southern hemisphere twice-daily satellite infrared cloud mosaics for the five winters (June through September) of 1973–77, using the Troup and Streten (1972) vortex classification system, has yielded a winter climatology of cyclonic activity (Carleton 1979a, 1980, 1981a, b). This complements the earlier study by Streten and Troup (1973) for summer and the transition seasons.

Cyclogenetic (W,A,B) vortices

According to the Troup and Streten (1972) classification scheme, satellite-observed extratropical cyclogenesis may occur either in association with a pre-existing frontal cloud band (the wave, or ‘W’, type), or as an isolated comma-shaped cloud mass (the ‘A’ type). A third, less frequent, form of cyclogenesis (the ‘instant occlusion’) results from the merging of a ‘W’ development with an ‘A’ vortex (Zillman and Price 1972). The winter-season climatology of this phenomenon is treated elsewhere (Carleton 1981b). Continued development of the frontal wave and comma cloud vortices, manifested on the imagery by the appearance of a hook-shaped cloud feature with accompanying clear slot, is classified as a ‘B’-stage vortex (Troup and Streten 1972). In this study, the W, A, and B stages are grouped into one general cyclogenetic class. The mean winter (1973–77) distribution of these vortices is shown in Fig. 1, and indicates maximum frequencies in the Indian Ocean and the South Pacific and Atlantic oceans, in association with the major climatic fronts (Carleton 1979a, 1981a). These patterns resemble those found for the other seasons (Streten and Troup 1973), but with an additional zone of higher-latitude cyclogenesis located in the South Pacific in winter, and more pronounced cyclogenesis through the Tasman Sea. The South Pacific zone, corresponding to Taljaard’s (1968) Winter Antarctic Front (WAF), is the site of frequent ‘inverted comma’ (A) systems as opposed to the predominantly frontal wave (W) developments characteristic of the middle-latitude regions of cyclogenesis (Carleton 1981a). The existence of the WAF, together with the high frequency of wave developments at lower latitudes, gives rise to a latitudinally bimodal distribution of cyclogenesis in the Pacific sector (Fig. 2) that is less marked in the other quadrants (Carleton 1979b).

Figure 1 shows the regions of winter cyclogenesis to be located close to the Oceanic Polar Front (OPF), a zone of steep latitudinal tem-
Fig. 1 Mean monthly distribution of cyclogenetic (W,A,B) cloud vortices for winter (1973–77), and relationship to the OPF (dot-dashed line), and mean positions of the sea-ice margin for June (heavy dashed line) and September (heavy solid line). Isopleth values refer to area-normalised frequencies in each 5° latitude by 10° longitude unit. The total (five-winter) number of W,A and B vortices for the hemisphere is 10,974. From Carleton (1981a).

perature gradients (Zillman and Dingle 1973). Strong ocean-atmosphere coupling is therefore a feature of winter as of the other seasons (Baker 1979), particularly in the vicinity of the major hemispheric long-wave troughs. It is noted that the cyclogenetic maxima lie generally on the equatorward side of the OPF, due chiefly to the reversal of sign of the oceanic heat flux from south to north (Taylor, Gordon and Molinelli 1978), and may indicate the generation of thermally-direct mean meridional circulations important in jet stream development (Physick, in press). Conversely, the locations of the oceanic polar fronts are partly determined by the cyclonic activity regimes (Baker 1979). The coupled surface-atmosphere regime shown in Fig. 1 indicates the dominance, in the southern hemisphere mean pressure field, of wave number one through its apparent relationship with the asymmetric sea surface temperature distribution, a feature noted earlier by Anderssen (1965).

At high latitudes of the South Pacific, the influence of the OPF on cyclogenesis is augmented by the relatively conservative winter sea
Fig. 2 Mean (five-winter) distribution of the frontal wave (W) and 'inverted comma' (A) cyclogenetic vortices for the Pacific (180°-90°W) sector (top) and Australian (90°E-180°) sector (bottom). Frequencies in each 5° latitude band are expressed as the percentage of the total for each type over all latitudes in that sector. Figures in brackets give total numbers of vortices for the five winters.

ice regime (Carleton 1981a). This enhances the development of a seasonal baroclinic zone at the ice limit which favours in situ cyclogenesis of the comma cloud (A) type in polar air outbreaks northwest of the Ross Sea and in longitudes of the Bellingshausen Sea (Fig. 1). Such ice-ocean-atmosphere linkage resembles that occurring in the northeast Atlantic during winter, which also gives rise to frequent 'polar low' developments (Rabbe 1975).

**Mature/dissipating (C and D) vortices**

Figure 3 gives the mean (five-winter) distribution of the mature/dissipating (combined Streten-type C and D) vortices. The cyclonic maxima over the Antarctic oceans, which delimit the 'circumpolar trough' (van Loon 1967), indicate the importance for cyclolysis of the major embayments (Carleton 1979a), and hence are key regions for ice-ocean-atmosphere interaction (Streten and Pike 1980). An exception is the major vortex area north of Wilkes Land (Fig. 3). It is noted that the circumpolar trough in winter lies generally poleward of the pack-ice margin. The cyclone patterns shown in Fig. 3 result from the general southeastward movement towards higher latitudes of the cyclogenetic vortices, with the major exception of those associated with the WAF. In this case, the frequency maximum of mature vortices located in the Bellingshausen Sea (Fig. 3) results from the merging tracks of cyclones of lower latitude origin and those forming in situ at the region of the WAF (Carleton 1981a). The cyclonic maximum in the Weddell Sea may reflect the stationarity of dissipating depressions rather than being an area of true mean low pressure (Streten and Wells 1977; Carleton 1981a). The cyclolytic areas of
Fig. 3 Mean monthly distribution of mature/dissipating (combined C and D) cloud vortices for winter (1973–77). Frequencies are area-normalised as in Fig. 1. The total (five-winter) number of C and D vortices for the hemisphere is 12,823.

Vortex dissipation located north of the Ross Sea and in the Bellingshausen Sea show the greatest interannual variability in cyclone frequencies for the 1973–77 winters, in contrast with the more conservative maximum north of Wilkes Land (Carleton 1979a). The impact on the regional sea ice regime of such variations in intensity of the circumpolar trough for two case-study winters is considered below.

**Within-season variations of cyclonic activity**

Cyclonic vortices of all types are observed to be about two and a half times more frequent in the winter months than in summer. Highest frequencies for the hemisphere occur in August (average 1224; standard deviation of 326), with September having the least (average 1124; standard deviation of 262). Significant variations in cyclone frequencies as a function of latitude have been determined (Carleton 1981a). The maximum equatorward extent of cyclonic activity occurs in July (40–49°S), with September having the most poleward location (60–75°S). These seasonal variations in the circumpolar trough create the winter/early spring maximum of the semi-annual pressure oscillation over sub-Antarctic latitudes (van Loon 1967). Thus, while Schwerdtfeger and Kachelhoffer (1973) show that hemispheric-scale variations in cyclone frequency between autumn and spring are apparently related to the seasonal expansion of the Antarctic sea ice, this is not the case during winter, when the circumpolar trough migrates polewards during the period of continuing ice advance.

Regional variations in the magnitude of the semi-annual oscillation are apparent, as shown by the intensification of the major higher latitude centres of cyclogenesis and cycloysis between June and September (Carleton 1981a). Between these months, cyclonic activity generally decreases over middle latitudes, particularly in the southwestern Pacific, in association with the greater variability of westerly flow and an increased incidence of anticyclonic blocking in late winter and spring (Streten 1977, 1980b).
Ice-ocean-atmosphere interactions for the winters of 1974 and 1976

Surface-atmosphere interactions at high southern latitudes are now examined for the two winters of most contrasting hemispheric cyclone activity during the period 1973–1977. In this way, the contribution of cyclones to the interannual variations in ice extent exhibited on a regional scale may be assessed. The winters of 1974 and 1976 were the most different both in terms of the total numbers of cyclones occurring, where frequencies for 1976 were only 60 per cent of those for 1974, and in the dominant latitude zones frequented by the different Streten vortex types. In the Australian sector (90–180°E), for example, there was a southward shift in the frequencies of cyclogenetic vortices of the order of 5 to 10° of latitude in the 1976 winter compared with winter 1974 (Carleton 1980). Interannual variations of this type appear to be commensurate with fluctuations in the seasonal location and intensity of the major longwave troughs.

Sea ice conditions, 1974 and 1976

Fleet Weather Facility (FLEWEAFAC) analyses were used to obtain weekly positions of the sea ice edge for the two winters, measured at every 5° of longitude. Table 1 shows that the zonally-averaged ice edge in the 1974 winter was located further equatorward than for the corresponding months of 1976.

Figure 4(a) indicates that these zonal values mask substantial regional variations and a clear inter-relationship between the different sectors (Budd 1975; Zwally et al. 1979a, b). The greatest differences occurred north and east of the Ross and Weddell Seas, where the 1974 ice extent was particularly large, and for longitudes of East Antarctica from 10 to 110°E and the Bellingshausen Sea (100 to 60°W), where the 1976 season had the more extensive ice cover. The timing of the maximum zonally-averaged ice extent for 1974 occurred in September, but in the 1976 season there was virtually no increase (+0.1° lat.) between August and September (Table 1). As the maximum ice extent normally occurs in September and October (Streten and Pike 1980), the anomaly represented by late winter 1976 implies a substantial change in the contribution of the pack-ice zone to the seasonal surface energy budget of the southern oceans (Weller 1980). The longitudinal variability of the monthly zonal mean ice extent, given by the standard deviations in Table 1, is greater during the 1976 winter after June than for the corresponding months of 1974.

Ice variations as a response to high-latitude cyclonic activity

Figure 5 shows the differences in total vortex frequencies (all types) poleward of 40°S for the 1976 winter expressed as a percentage of those for 1974. Winter 1976 was characterised by generally reduced cyclonic activity, except in certain higher latitude regions of the southern oceans and coastal Antarctica. Interannual variations in the ice-edge advance for the East Antarctic sector are likely to be a response to changes in the atmospheric circulation, as ice growth in this region is more strongly controlled by thermodynamic than dynamic processes (Ackley 1979). Thus, the greater equatorward extent of the ice in 1974 for longitudes 100 to 150°E (Fig. 5) was associated with fewer cyclones in that region, implying generally lighter winds in the season of ice advance (Streten and Pike 1980), compared with 1976. Marked surface-atmosphere coupling is evident for the Weddell Sea sector between 30°W and 10°E (Fig. 5), but the dominant direction of this feedback is not clear. Thus, 1976 increases in cyclonic activity in the vicinity of the Weddell ice edge imply either direct forcing by the atmosphere, or enhanced cyclogenesis/cyclonic intensification as a result of the increased oceanic heat loss, or both.

Figures 4 (a) and (b), showing the interannual variations in vortex frequencies (all types) for the latitude zone generally occupied by the circumpolar trough (50–70°S), indicate further the regional associations between the atmospheric circulation and the winter sea ice regime evident in Fig. 5. Examination of Fig. 4 also confirms the observation by Streten and Pike (1980) that the ice edge tends to advance to the west of longitudes having a high frequency of depression centres. Thus, the

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Fig. 4 Mean positions of the Antarctic sea ice margin (a), together with cyclonic vortex frequencies (all types) in the 50 to 70°S zone (b) for the winters of 1974 and 1976.
Fig. 5 Vortex frequencies (all types) for the 1976 winter expressed as a percentage of those for winter 1974 poleward of 40°S. Stippled areas highlight greater 1976 cyclonic activity. Mean location of winter sea ice margin for 1974 given by solid heavy line, and for 1976 by heavy dashed line.

much greater frequency of vortices in the Bellingshausen Sea sector in 1974 (Fig. 4(b)) appears to have produced the more equatorward seasonal mean location of the ice margin by enhancing ice advection east of the Ross Sea (Fig. 4(a)). Atmospheric controls are known to be of major importance in determining the winter ice regime of the Bellingshausen-Amundsen sectors (Ackley 1981). Similarly, a peak in the cyclonic activity for the 60 to 40°W sector in 1976 (Fig. 4) was associated with greater equatorward extent of the ice from 100 to 60°W in that winter.

An indication of the longitudinal frequency of sub-Antarctic high pressure ridges for the two winters is given in Fig. 4(b) by the negative (unshaded) peaks in the cyclonic activity index. A relatively high frequency of anticyclonic ridges is apparently connected with an ice margin that shows little within-season variation and which remains located at relatively high latitudes (Streten and Pike 1980). This is seen to occur in 1974 (Figs 4(a) and (b)) between about 20 and 80°E, and in 1976 for the longitudes of the Ross Sea eastward to the Amundsen Sea (180–110°W). However, this association is not evident for longitudes north and east of the Weddell Sea (Figs 4(a) and (b)), where a much more equatorward regional ice extent in winter 1974 is coincident with a relatively high frequency of subpolar ridge activity between 30°W and 0° compared with 1976. This confirms, instead, the overriding importance of the oceanic circulation to ice distribution in this region (Schwerdtfeger 1979; Streten and Pike 1980; Lemke et al. 1980).

Figure 6 shows the change in sea ice extent between June and September, and indicates general ice advances for both winters, with the exception of certain longitudes of the Ross Sea sector. This advance was most pronounced north and east of the Weddell Sea and northeast of the Ross Sea, which are areas of marked interannual variability in ice conditions (Jacka 1981) and where ice advection effects are known to be particularly important (Zwally et al. 1979a, b; Streten and Pike 1980; Ackley 1979; Lemke et al. 1980). The peak in the Weddell Sea sector was displaced some 20 to 25° further west in 1976, and is related to the later closing-off of the major recurring polynya in that winter. The large seasonal variation in ice extent for the Weddell Sea (Fig. 6) has
been shown to be responsible for the greater variability of monthly mean temperatures experienced by the islands in the Scotia Sea compared with islands at similar latitudes elsewhere in the hemisphere (Streten 1977; Budd 1981). Also in Fig. 6, the major cyclonic frequency maxima for the 50 to 70°S zone are superimposed on the seasonal patterns of change in sea ice extent for the 1974 and 1976 winters. It is seen that the increase in ice extent between 30 and 60°E in 1976 was larger than in the 1974 winter. This is explained by the greater cyclone frequencies occurring to the east in 1976. The anomaly in the Ross Sea sector for 1974, where greater ice extent occurred in June rather than September, was suggested by Zwally et al. (1979b) as being due to marked early-season ice advection eastward into the Amundsen and Bellingshausen seas (Zwally et al. 1979b), and is apparently confirmed by the location of the cyclonic activity peak between 110 and 70°W (Fig. 6). However, this explanation is disputed by Ackley (1981) from consideration of the dominantly westward, as opposed to eastward, movement of ice occurring between these two regions, and is also consistent with the results of Lemke et al.'s (1980) analysis of the space-time structure of sea ice anomalies. They show a marked westward advection of ice anomalies for the Weddell and Ross seas, and north of the Amery ice shelf, with a generally eastward translation apparent elsewhere, especially east of the Weddell Sea, in the southern Indian Ocean and Amundsen Sea.

Cyclogensis in relation to sea ice variations

It was suggested earlier that the relatively conservative winter sea ice regime in the South Pacific sector may exert synoptic-scale forcing on the atmosphere by enhancing high-latitude cyclogensis. This relationship is now examined for the interannual ice variations between the 1974 and 1976 winters. Figure 7 gives the cyclogenesis patterns (combined 'W' and 'A' types) for three latitude zones (40–50°S; 50–60°S; 60–70°S). Greater longitudinal variation in cyclogensis is evident for the 1976 winter, especially at high latitudes. The marked peak at 60 to 70°S for the Ross Sea sector in 1976, which was absent in 1974, is related to the more southward ice margin in this region (Fig. 7). In this sector in the 1974 winter, a greater percentage of cyclogenesis occurred in the 50 to 60°S zone, in accord with the more equatorward ice margin and its closer proximity to the OPF. Similarly, high-latitude cyclogensis increased in 1974 east of the Ross Sea through longitude 100°W with the more extensive ice in that region compared with 1976. A peak in cyclogenesis between 110 and 100°W (60–70°S) is evident in both winters (Fig. 7), and was associ-
Fig. 7 Cyclogenesis (W and A vortices) in three latitude zones (60–70°S: shaded; 50–60°S: blank; 40–50°S: stippled), winters 1974 and 1976. Frequencies in each zone expressed as percentage of total cyclogenesis between 20 and 70°S for that 10° longitude sector.

1974

1976

ated with their comparable ice extents shown in Fig. 4(a). The strong increase in cyclogenesis in 1976 from about 100 to 60°W between 50 and 60°S did not occur in this zone in 1974, and was apparently related to the more equatorward location of the ice margin in this sector in 1976 (see Fig. 4(a)). Considerably greater relative frequencies of new cyclonic developments in the ice-edge latitude zone also occurred during 1976 between longitudes 70 and 100°E. While these may be related to the greater equatorward location of the ice margin in this sector (Fig. 4(a)) and to the marked equatorward increase of ice extent between June and September for these longitudes (Fig. 6), the steep thermal gradients of the OPF are located considerably more north in this region than in the South Pacific (Fig. 1). In this case, a more likely explanation is to be found in the increased frequency of polar air outbreaks and associated in situ cyclogenesis near the ice margin, expected as a result of the high frequencies of dissipating depressions located further east (90–140°E) in this winter (Fig. 4(b)).

Cyclogenesis in the 40 to 50°S zone is related more to the OPF in the preferred regions of the hemispheric long-wave troughs than to baroclinicity at the ice edge (Carleton 1981a). This is particularly evident in Fig. 7 for the Indian Ocean sector, where the more westward displacement of activity in 1976 compared with 1974 was expressed in substantial winter rainfall anomalies over southern Australia (Carleton 1980). Similarly, cyclogenesis was considerably reduced in winter 1976 from that for 1974 in the central and eastern Pacific (Fig. 7).

Synoptic-scale influences of the Weddell Polynya

The advent of satellite sensing in the microwave range, which facilitates all-weather and all-seasons surveillance of higher-latitude snow and ice regimes, has shown that estimates of ice/water concentrations for the Antarctic winter pack are considerably lower than those made previously (Ackley 1981). Weller (1980) indicates that these new data may necessitate revision of seasonal estimates for oceanic energy losses in the sea ice zone and their interannual variation. The existence of open-water polynyas within the ice boundary are particularly critical for these gross esti-
mates of air-sea interaction (Streten and Pike 1980) and for the modification of regional climate. The presence of a large recurring polynya in the Weddell Sea sector in late winter and spring, which accounts for about half of the total interannual variability of the Antarctic pack (Zwally et al. 1979b), is known to be of major meteorological significance (Carsey 1980). From the microwave data, this polynya covers approximately 2 to 3 x 10^6 km^2 (Carsey 1980). It forms by the closing-off of a major ice tongue advected northeast during the autumn and winter. Possible reasons for the persistence and short-term behaviour of this feature are discussed by Carsey (1980).

The areal extent of the polynya raises the question of its possible synoptic-scale effects on the atmospheric circulation of the Weddell Sea region. It has already been shown in Fig. 5 that the Weddell ice margin is a key area for ice-ocean-atmosphere interaction in winter as manifested by the cyclonic activity patterns. Figure 8 shows the area-normalised distributions of the cyclogenetic (W,A,B) vortices for the three winters of 1973, 1974, and 1975, together with the September ice margins determined from the microwave imagery and given by Carsey (1980). The Weddell polynya forms in most winters, as it did in 1974 and 1975, but was absent in 1973. The September positions of the polynya for 1974 and 1975 are also given in Fig. 8. It is noted from Fig. 8 that the frequency of new cycloic developments in the vicinity of the polynya is substantially greater in both the 1974 and 1975 winters than for the same region in winter 1973. The displacement of the cyclogenetic maxima to the east of the September polynya position is compatible with the westward drift of this feature observed during the winter months (Carsey 1980). The patterns shown in Fig. 8 thus imply considerable synoptic influence of the polynya, through increased oceanic heat loss, on the seasonally-averaged high-latitude circulation of the Weddell region.

**Concluding remarks**

Use of a satellite-derived index of cyclonic activity shows that ice-ocean-atmosphere interaction over the southern oceans in winter is significant on seasonal and interannual time scales. Anomalies between years in the total areal extent of the Antarctic pack and monthly changes during the growth period may be substantial from an energy budget standpoint. Interannual variations in cloud vortex frequency and its longitudinal distribution, particularly those in the later stages of cyclonic evolution occurring at the higher latitudes, influence not only the regional extent of the Antarctic sea ice, but also the relationship between adjacent sectors through ice advection. On the other hand, a more equatorward regional ice extent in a given winter tends to increase cyclogenesis in the ice-edge latitude zone through enhanced baroclinicity. Similarly, the presence of a large open-water polynya in the Weddell Sea sector in winter appears to modify substantially the regional atmospheric circulation by increasing high-latitude cyclogenesis. It seems imperative, therefore, that future modelling of ice-atmosphere interactions attempt to incorporate these complex synoptic-scale feedbacks evident at higher latitudes of the southern oceans. Similar satellite-based studies are currently in progress for the North Polar region.

**Acknowledgments**

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**References**


Fig. 8 Mean monthly distribution of cyclogenetic cloud vortices for the South Atlantic, southwest Pacific, and southern Indian oceans for the winters of 1973, 1974 and 1975. Vortex frequencies are area-normalised to 45°S. The locations in September of the sea ice boundary (heavy solid line) and the Weddell Polynya (shaded) are also shown for the relevant winters.