Antarctic Science 5 (2): 221–226 (1993)

Evidence for an Antarctic winter coastal polynya

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Abstract: Satellite infra-red imagery and meteorological data suggest the presence of winter open water (polynya) in the coastal pack ice to the north and west of the Brunt Ice Shelf. Satellite imagery, although only available for a limited number of occasions, provides evidence for the polynya during the austral winter of 1991. Indirect meteorological observations from the British Antarctic Survey's Halley station (75° 36'S, 26° 42'W) provide very strong supporting evidence of open water to the west of the ice shelf in previous years.

Received 17 June 1991, accepted 18 April 1992

Key words: polynya, sea ice, fogs, meteorology, Weddell Sea

Introduction

This paper describes evidence for the existence of a perennial winter polynya off the Brunt Ice Shelf in the Weddell Sea (Fig. 1). Polynyas are areas of open water in otherwise closed pack-ice, and can occur both at the coast, where the sea ice borders either the mainland ice shelves or fast ice (coastal polynyas), or within pack-ice covered oceans (offshore polynyas) (Gordon & Comiso 1988). Polynya formation is governed by two mechanisms, which are not mutually exclusive: ice removal by wind/ocean currents (latent heat polynyas) and prevention of ice formation by ocean turbulence/upwelling (sensible heat polynyas). In latent heat polynyas the heat liberated as ice is formed limits the rate of ice production, allowing wind forcing to remove new ice from the polynya.

Antarctic polynyas have been studied using a variety of satellite borne sensors (Comiso *et al.* 1987) and occasionally using ships (Eicken *et al.* 1986). Polynyas affect air/sea energy and moisture exchange, salinity profiles and biomass behavior. The small relative sizes of typical polynyas within vast areas of ice cover is more than compensated by their vigorous interaction with the atmosphere and ocean. Energy transport from ocean to colder overlying air can be up to two orders of magnitude greater than in the surrounding regions where the intervening sea ice decouples the surfaces (Kottmeier & Engelbart 1992). Infra-red (IR) images from satellite borne instruments can be used to detect open water within sea-ice, even during winter darkness, although short wave IR images of the type presented here often have surface features obscured by cloud cover.

Two recurring coastal winter polynyas are reported, both near the British Antarctic Survey's (BAS) Halley station. Daily satellite images from Advanced Very High Resolution Radiometer (AVHRR) for the Brunt Ice Shelf are available for 1991. Local meteorological data dates back to 1957. Using these data, the occurrence of certain fogs during 1991 are shown to be associated with a local polynya. Analysis of the climatology of these fogs is then shown to indicate that 1991 was not unique in having local open water throughout most of the winter months.

Data sources

Low resolution real time AVHRR data was received by a British Aerospace Dartcom System satellite imagery system receiver from the NOAA 11 and NOAA 12 polar orbiting satellites. The AVHRR images were processed on the ARAMIS system (Turner 1987) but since software for the calibration data was unavailable during 1991 the images can

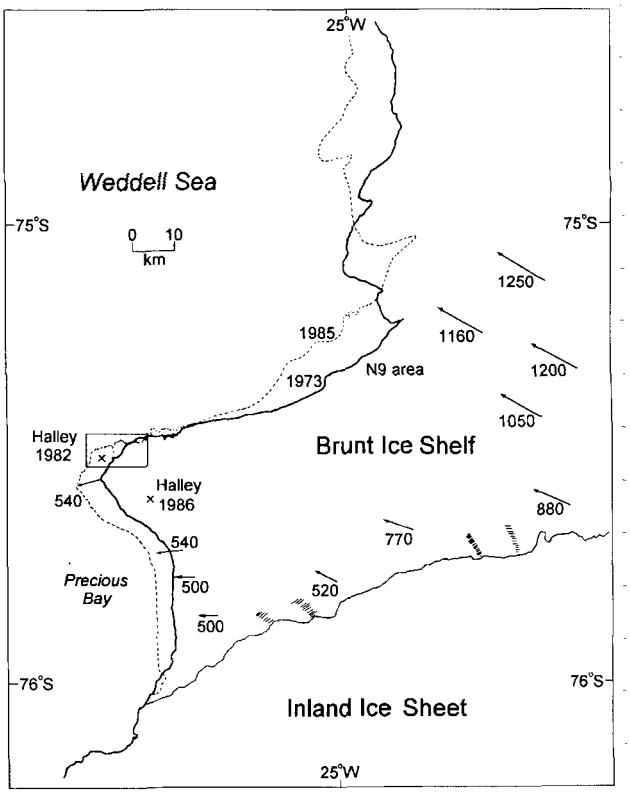


Fig. 1. A map of the Brunt Ice Shelf in the vicinity of Halley station, showing some of the locations mentioned in the text. Arrows denote ice shelf movement in metres per year. The box around the 1982 Halley position is shown expanded in Fig. 2.

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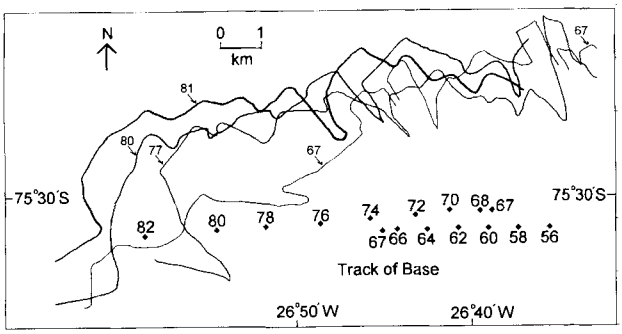


Fig. 2. Detail from Fig. 1 showing the effect of ice shelf movement on base position relative to the coast. The base was rebuilt in 1967. The coast lines show that the ice edge breaks off at a similar rate to the ice shelf movement.

only be interpreted qualitatively. Two typical images are shown in Figs 3 & 4, for easterly winds and strong westerly winds respectively. These images both display a warmer surface temperature between the ice shelf and the inland ice. This effect is often seen at the junction of ice shelves with the continental ice sheet, and surveys of these areas confirm that the warming cannot be due to thin ice or polynyas. Local surveys of the Brunt Ice Shelf grounding line south east of Halley have observed katabatic winds flowing north west off the rising continental ice sheet. Within a few kilometres north of the grounding line, these winds are no longer noticeable at ground level. Such winds would enhance mixing within the boundary layer. The IR images were taken in winter when the lack of overlying cloud would guarantee a strong inversion over the ice shelf (King & Anderson 1988). Enhanced mixing reduces the inversion temperature gradient, and so gives an elevated surface temperature between the ice shelf and the land.

The 1991 data show variation of sea ice over a single winter. Lower resolution calibrated satellite IR data for 1 July 1984 for the same area (Fig 5) gave a polynya surface temperature of 0°C±2°C, and so confirming open water for that occasion. Comparison with the 1991 data helped to distinguish true open water from pack or thin ice cover.

Satellite passes during 1991 have been chosen corresponding to days when no cloud cover was reported at the station. In addition, data were limited to the months May to August inclusive, this being the coldest part of the winter when ice production in any coastal leads would be greatest.

The three hourly synoptic surface meteorological observations from 1957 onwards were used for climatology. Although these data are continuous from 1957, care is needed in interpretation of any trends seen. Due to ice shelf

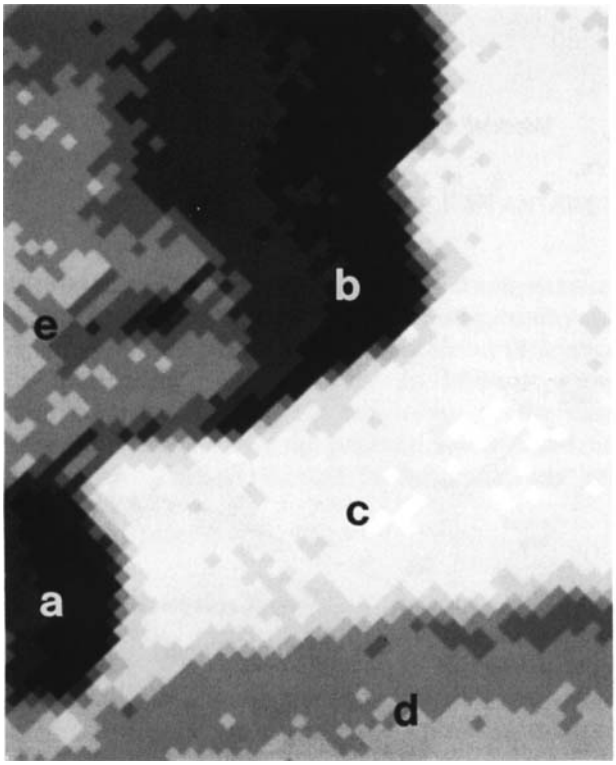


Fig. 3. AVHRR image for 1 June 1991 of the same area as Fig. 1. The image shows (a) polynya Precious Bay, (b) polynya at N9, (c) Brunt Ice Shelf, (d) inland ice, and (e) sea ice.

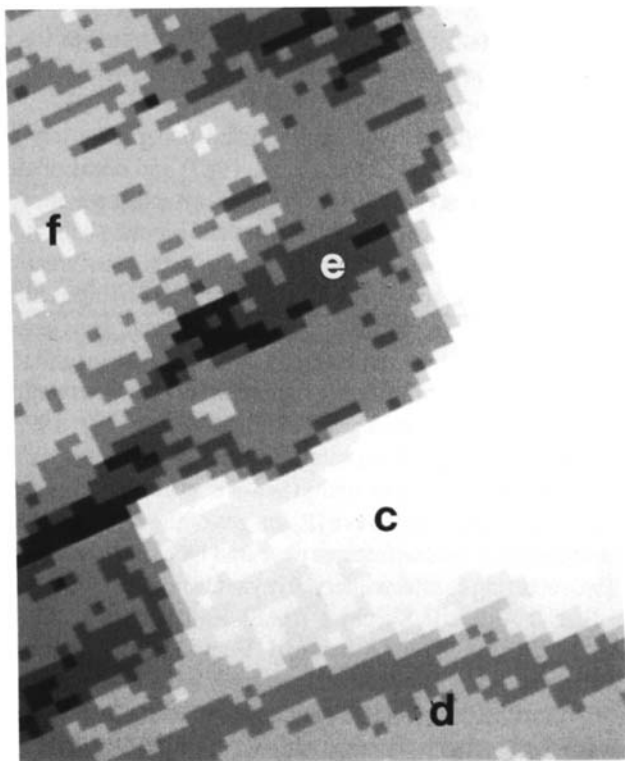


Fig. 4. AVHRR image for 21 July 1991, showing partial ice covering of Precious Bay area. Areas are designated as for Fig. 3, with thin sea (e) and thick sea ice (f).

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movement accompanied by ice front calving at a similar rate, the base position with respect to the coast changes each year. Shelf movement is *c.* 500m y^{-1} due west at Halley (Simmons 1986, Simmons & Rouse 1984). In addition, snow accumulation necessitates the rebuilding of the base periodically. Fig. 2 shows the positions of the coast and stations I–III. Halley IV, built further south, was last occupied in 1991.

Results and discussion

Satellite data

IR images are difficult to interpret, as the indicated temperature is not necessarily that of the surface. Overlying cloud is opaque to IR and will give its own radiation temperature. In addition, during winter, the actual coast can be difficult to determine, due to similar surface temperatures of ice shelf and pack ice. Areas of open water smaller than the resolution of the data (4 km), and partially open pack ice, will be averaged to give an indicated temperature less than 0°C. The satellite imagery from 1986 and 1991 show areas to the west and north of Halley much warmer than either the sea-ice or ice-shelf surface temperature (Figs 3, 4 & 5). The 1986 data gives the temperatures as 0°C±2°C. Although the 1991 data

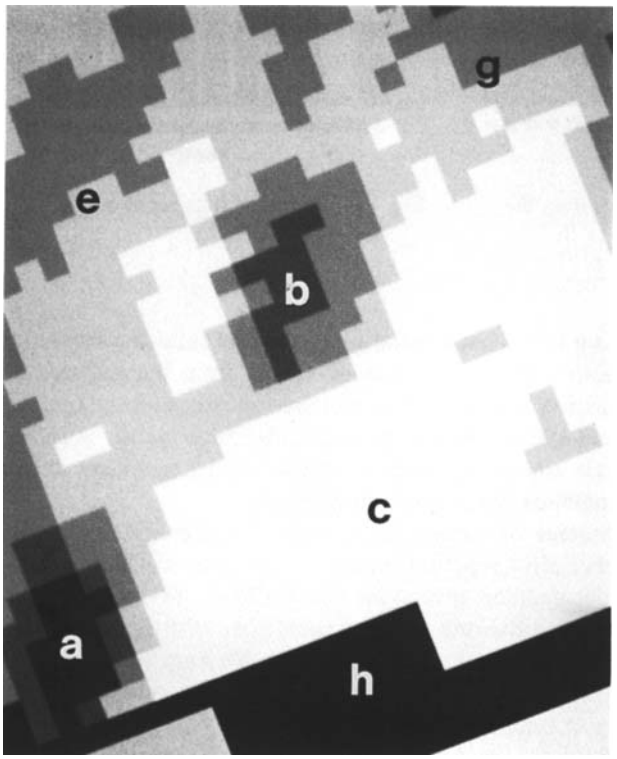


Fig. 5. Lower resolution calibrated AVHRR image for 1 July 1984 of the same area as Figs 3 & 4. The top right area (g) is obscured by cloud. The dark band (h) is an overlaid coastline. Other areas are as in Figs 3 & 4.

Table I. Wind speed and direction for satellite images 1991.

Day	speed	direction	polynya state precious	N9	fog at Halley
May 09	3.7	120	open	part open	no
May 10	2.5	80	open	open	no
May 12	5.2	70	open	open	no
Jun 01	2.9	70	open	open	no
Jun 27	4.6	80	open	part open	no
Jul 15	1.9	170	part open	part open	in distance
Jul 21	6.7	230	cover	cover	yes
Jul 22	0.9	70	cover	cover	no
Aug 05	5.3	250	cover	cover	yes
Aug 09	0.8	270	cover	cover	in distance
Aug 28	13.8	80	open	open	no

are qualitative, it is fair to assume that the warm areas are open water, due to the very large sea-ice/'polynya' temperature difference, and the similarity with the 1986 image.

A few of the 1991 images showed the polynyas to be partially ice covered as seen by a comparable temperature range over the polynya area compared to more northern sea ice. Table I catalogues the images selected for days when no cloud cover was observed at Halley and shows the correspondence between wind direction and polynya state. The polynyas are seen to be covered when accompanied by westerly wind vector averages over the day. The exception is July 22 1991, having a low easterly average, but this occurs directly after a day of strong westerlies. Fig. 4 shows a typical closed polynya, in that the area is not clear of ice. Although Table I refers to 'ice cover', the surface temperature of this coverage is still warmer than the surrounding pack-ice, implying thin or broken ice cover.

The table also shows the correspondence between wind direction and fog occurrences. Fog is reported at or near the base when the wind is from the west, even when the satellite image shows the upwind polynya to be thinly ice covered.

Kottmeier & Engelbart (1992) show that wind forcing dominates ocean current forcing as the mechanism for polynya formation along the Brunt Ice Shelf in summer and the above data supports this for the winter because the the polynya tends to open during periods of easterly or light westerly winds, but closes during periods of strong westerly winds. This implies that latent heat is the dominant mechanism involved. The Weddell gyre (Limbert *et al.* 1989) may assist the process of new ice removal, with possible upwelling in the lee of promontories adding sensible heat from deep water layers (Kottmeier & Engelbart 1992).

Meteorological data

The local effects of open water near Halley are water sky and sea smoke (WMO 1970) during hours of daylight when the effects can be seen. Very occasionally, water sky has been observed by moonlight, given suitable cloud conditions.

Analysis of the meteorological data, with emphasis on fog

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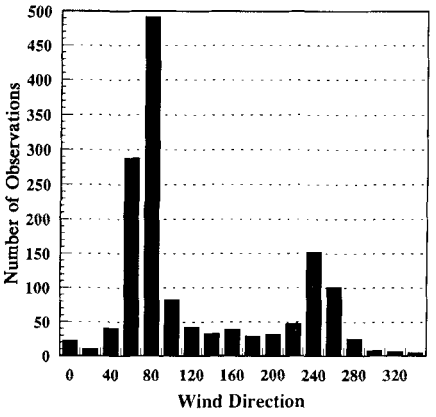


Fig. 6. Wind directions for winter 1991.

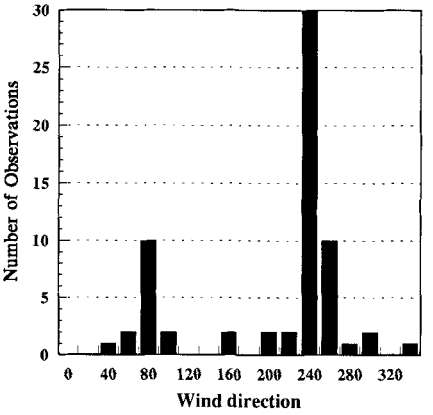


Fig. 7. Wind directions for fogs during winter 1991.

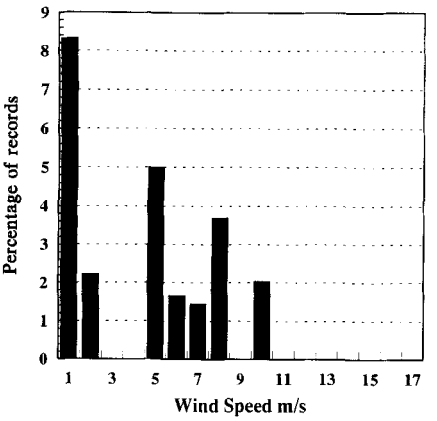


Fig. 8. Percentage of winds with fog from the east as a function of wind speed.

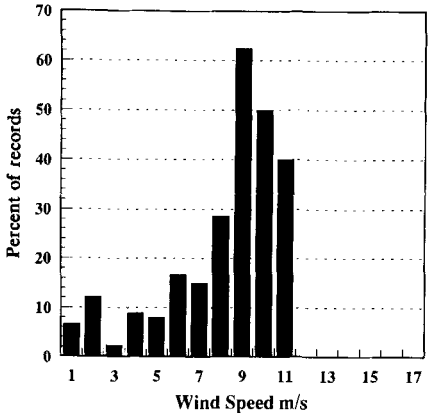


Fig. 9. Percentage of winds with fog from the west as a function of wind speed.

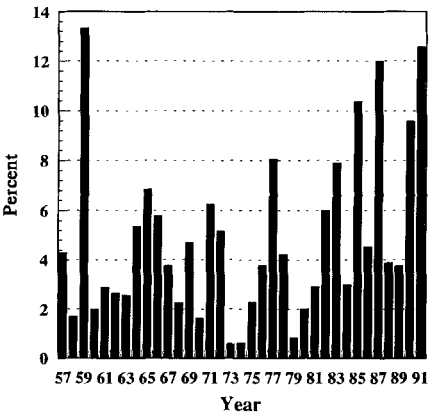


Fig. 10. Percentage of winds from the west bearing fog.

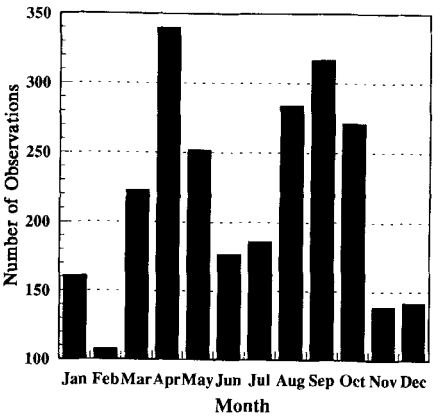


Fig. 11. Number of fogs per month for years 1957–1991.

occurrences, provides a climatology showing no significant change from 1991. At Halley, fog is recorded when visibility is reduced below 1km and the reduction in visibility is not due to precipitation or blowing snow (WMO 1988). Local supercooled water fogs occur at the station during the winter and data presented below suggest that fogs accompanying westerly winds are due to advected moist air/sea smoke, rather than being solely caused by radiative cooling and subsequent condensation.

Open water in otherwise close pack-ice injects moisture into the overlying atmosphere. With surrounding air temperatures well below 0°C, strong convection takes place over the water. Mixing and cooling of the rising air will result in condensation, and the whole effect is termed sea-smoke, due to the appearance of these processes. Once the moist air is advected away from the polynya, the source of instability is removed, and a more homogeneous fog results. At Halley, inversions occur often, due to radiative cooling of the surface (King 1990). Stable stratification of the boundary layer traps fog to within a few tens of metres from the ground, and radiative loss from the top of the fog enhances the trapping (Stull 1988). With very weak turbulence found under very stable conditions, such a fog can persist for many tens of kilometres down wind of a polynya.

Studies of monostatic acoustic sounder (SODAR) data from Halley support the case for entrapment of turbulent fog under capping inversions (Culf 1989). SODAR data are corrupted at wind speeds in excess of 8 ms^{-1} at 8m, due to wind noise and so no information is available from these studies on well mixed flows. Culf also showed a predominance of such trapping conditions during westerlies.

Polar fogs may occur other than over polynyas. At Halley, radiative fogs could form irrespective of wind direction, as strong stability, due to radiative cooling, occurs in winter when the sky is cloud free and the wind speed sufficiently low to reduce turbulent mixing. Fig. 6 is a histogram of wind

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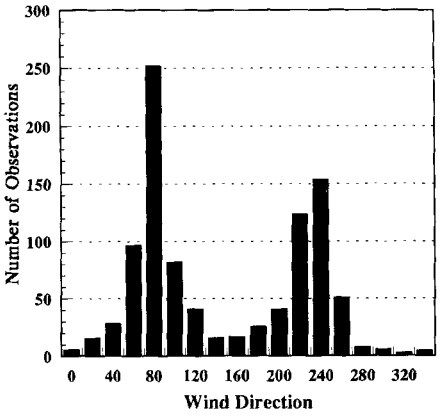


Fig. 12. Winter wind direction for days with fog for Halley I,II & III.

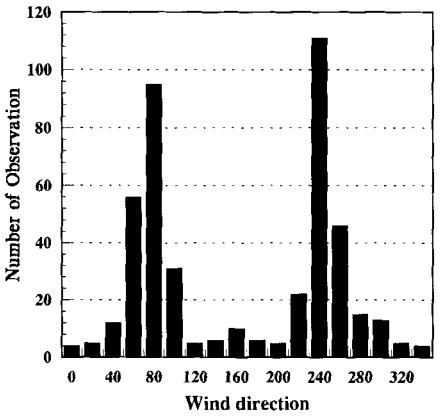


Fig. 13. Winter wind direction for days with fog for Halley IV.

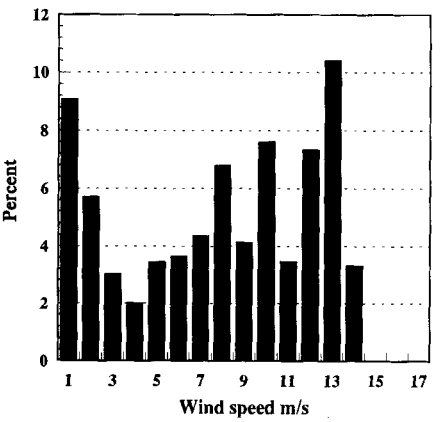


Fig. 14. Percent of winter westerlies with fog against wind speed for Halley I,II & III.

directions for 1991 and Fig. 7 shows the same data limited to occasions when fog was recorded. The strong tendency for westerlies to be accompanied by fogs is readily apparent. This tendency is also demonstrated in Table I for the limited occasions when suitable satellite images are available.

Figs 8 & 9 show the percentage of records with fogs against wind speed divided into easterly (50°–100°) and westerly (220°–270°) wind directions. Fogs associated with easterly winds are dependent on low wind speeds, unlike those associated with westerlies, which show increasing occurrences as wind speed increases up to 9 ms^{-1}. Above wind speeds of 12 ms^{-1}, the presence of drifting snow often confuses observation of any fog present, especially in winter. The reduction of occurrences could be due to observation error, strong mixing dispersing the fog, or onshore winds finally closing the polynya.

Despite the uncertainties when winds are in excess of 12 ms^{-1},the increase in fogs during westerlies supports the premise that these fogs are advected sea smoke rather than being radiative. They are therefore, most likely to be due to the Precious Bay polynya/thin ice seen on the IR imagery. The near lack of northerly and north east winds preclude the use of meteorological data to provide evidence for the N9 polynya.

Comparison of 1991 meteorological data to previous years

The total percentage of winds from the west bearing fog during winter is shown for each year in Fig. 10. Inter annual variation is very noticeable. No obvious trends are seen in the Halley I,II,III (up to 1982) data. Halley IV data do have a trend towards a higher percentage of fogs as the base nears the coast. The satellite images show the main polynya position to be still some distance south of Halley IV. The size of the polynya no doubt varies considerably from year to year, with

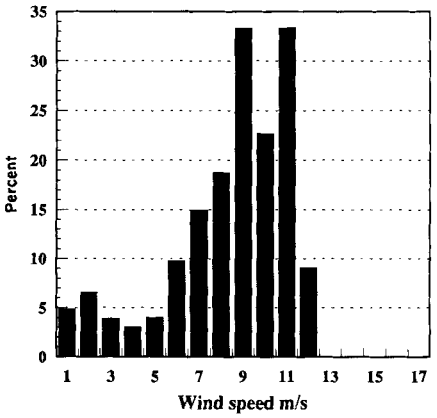


Fig. 15. Percent of winter westerlies with fog against wind speed for Halley IV.

the area of northern extent affecting the percentage of foggy westerlies. The more southerly position of Halley IV means that it will have experienced more occasions when the dominant westerly wind has passed over open water.

The whole data set (1957–1991) of winds associated with fog (Fig. 11) shows that most fogs occur in spring and autumn, with a slight reduction during the middle of winter. A possible explanation for this reduction is that the lowest temperatures occurring in mid winter enhance ice production in a latent heat polynya, and, given no other variation in wind speed etc, the polynya will reduce on average (Pease 1987). During summer, the air temperatures are nearer 0°C, and so air passing over ice will be in near thermal and moisture equilibrium after passing over open water and fogs are therefore less likely to occur.

Figs 12 & 13 show histograms of the number of records through winter associated with fog for the two main station positions (Halley I,II,III and Halley IV). Figs 14 & 15 show the wind speeds of the westerly records in Figs 12 & 13. As

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noted above, with Halley IV further south, there was a higher percentage of westerly winds associated with fog at this station, and the number of high wind speeds during fog conditions was greater. The trends seen from 1957 through to 1991 do not therefore suggest an increase in polynya frequency or area.

Conclusions

Meteorological data over more than 30 years, supported by more recent satellite data, show results consistent with a perennial, or near perennial coastal latent heat polynya to the west of the Brunt Ice Shelf.

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