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A pilot study on the interactions between katabatic winds and polynyas at the Adélie Coast, eastern Antarctica

UTE ADOLPHS and GERD WENDLER

Geophysical Institute, University of Alaska, Fairbanks, Alaska 99775, USA

Abstract: Infrared satellite images of the coastal area off Adélie Land were examined together with two wind data sets, one from the manned French station, Dumont d'Urville, the other one from an Automatic Weather Station (AWS) during the 1986 austral winter. A correlation between the development of open water areas (polynyas) and the appearance of extremely strong offshore winds can be drawn. The wind direction tended to be more perpendicular to the coastline during these extreme 'events', suggesting a katabatic origin of the increase in wind strength. In the study area the influence of the katabatic wind on the sea ice extends 20–100 km offshore. Sea ice motion further off the coast seems to be more dominated by synoptic scale weather systems. Broader scale atmospheric influences may create large polynya structures which influence the development of coastal winds, as the temperature contrast between open water and the cold continent generates its own circulation. Strong wind events can have a weakening effect on the coastal sea ice which can lead to a much more sensitive reaction of the sea ice in response to following anomalous wind events.

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Introduction

Sir Douglas Mawson (Mawson 1915) was the first to observe the very strong offshore winds along the coast of Adélie Land, eastern Antarctica, during his stay from 1911–1913 at Cape Denison, Commomwealth Bay. He recognized the winds as katabatic, i.e. winds caused by cold denser air falling down the slope of the Antarctic continent. The observed winds had annual mean speeds of *c.* 20 ms^{-1} and were the strongest found anywhere close to sea level on Earth. His data were doubted, but re-calibration of his anemometers after his return to Australia resulted only in minor adjustments.

Mawson found that the extremely stormy conditions at Cape Denison were connected with a less solid ice cover while at other stations, where the wind speeds are less extreme, there was unbroken sea ice cover during most of the winter. The strong offshore winds may even have predetermined Mawson's choice of Cape Denison as his main station since this ice-free area allowed him access to the coast. Mawson's sailing boat, with a steam engine as back up, did not have the ice strengthened capabilities of a modern day Antarctic-going vessel. The observations of wind and ice conditions in Adélie Land were later confirmed by the activities of the Expéditions Polaires Françaises (EPF) in the 1950's. At their main station, Port Martin, some 60 km to the east from Cape Denison, they observed similar wind conditions to those found by Mawson. During the winter 1950 and 1951 the mean wind was *c.* 18 ms^{-1} (Boujon 1954, LeQuinio 1956) although solid sea ice was observed for an unknown distance offshore. The highest monthly mean wind speed was found at this station with the extra ordinary value of 26 ms^{-1} (Loewe 1972). These high wind speeds were later outlined in greater detail by four AWS stations established along the Adélie Coast (Wendler & André 1991, Parish & Wendler 1991).

A thorough study of the movement of the sea ice in the archipelago of the station Dumont d'Urville, the former 'Pointe Géologie', was carried out by the EPF in 1952 (Rivolier & Duhamel 1956). The station was moved to this location after Port Martin burnt down. During their stay in austral winter 1952 a strong blizzard commenced on 31 August. Blowing snow restricted the visibility during this event to a few meters. After the wind speed had reduced on 2 September and hence the visibility had considerably improved, the French team discovered that the Isle des Pétrels was surrounded by an open water area without any ice. The meteorological situation during this event was characterized by a wind speed as high as 40 ms^{-1} on 1 September, accompanied by a lower than normal atmospheric pressure (956 hP) and higher than normal temperature (*c.* -15°C). When the storm abated to 9 ms^{-1} on 2 September, the pressure had risen to 982 hP and the temperature had dropped to -20°C. The event ended on 12 September when new sea ice had formed with an air temperature varying between -21°C and -24°C.

Observations of open water areas in sea ice are of great interest for atmospheric scientists, physical oceanographers and biologists (Anderson 1993, Kottmeier & Engelbart 1992, Pease 1987, Smith *et al.* 1990). For winter, the oceanic heat flux from open water areas is estimated to be one to two orders of magnitude higher than through the surrounding pack (Maykut 1978). Hence polynyas, leads

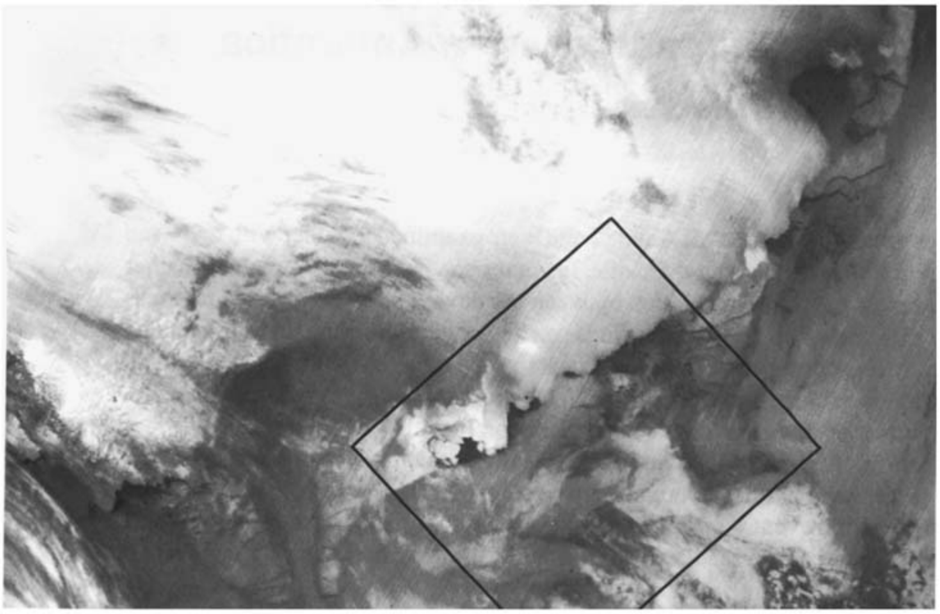


Fig. 1. IR image of 23 June, 0128 GMT, showing the sea ice conditions in the whole study area, which is indicated by the frame. Polynya area can be discriminated by its darker (black or dark grey) signature relative to the surrounding land or sea ice.

and thin ice, even if they are much smaller in area than the surrounding ice cover, can dominate regional heat budget fluxes in winter.

The oceanic heat flux to the atmosphere may be sustained by cooling the water (sensible heat) or by steadily forming new ice (latent heat), which might be mechanically removed by the wind. These two different energy sources also characterize the two principally different, mutually exclusive types of polynyas. In the case of a sensible heat polynya there might be a fairly large area of water maintained with practically no ice production. A latent heat polynya on the other hand, can be a relatively small open water area which persists in a steady state condition through the simultaneous actions of wind driven ice divergence and ice production. As ice is formed latent heat of fusion is released to the atmosphere and salt is rejected into the ocean. Thus ice production implies brine rejection in the latent heat type polynya. Since ice divergence is also the process which is responsible for lead formation, latent heat polynyas and leads are similar (Smith *et al.* 1990). However, leads have, in contrast to polynyas, no fixed locations, even if they are generally more prevalent in areas of thinner ice.

There are oceanographic reasons for the fact that sensible heat polynyas mainly occur in deep ocean regions, often initiating the process of deep ocean convection (Gordon 1981). A well known example of this is the Weddell Sea polynya. Latent heat polynyas, which are more frequent, are found to be mostly coastal features (Zwally *et al.* 1985). The water column is colder and hence energy release is provided by ice production. Thus polynyas effect atmospheric as well as oceanographic conditions. Since the atmosphere, as well as the ocean, may serve as long range means for transporting energy or matter, polynyas are also of importance for questions about global climate change.

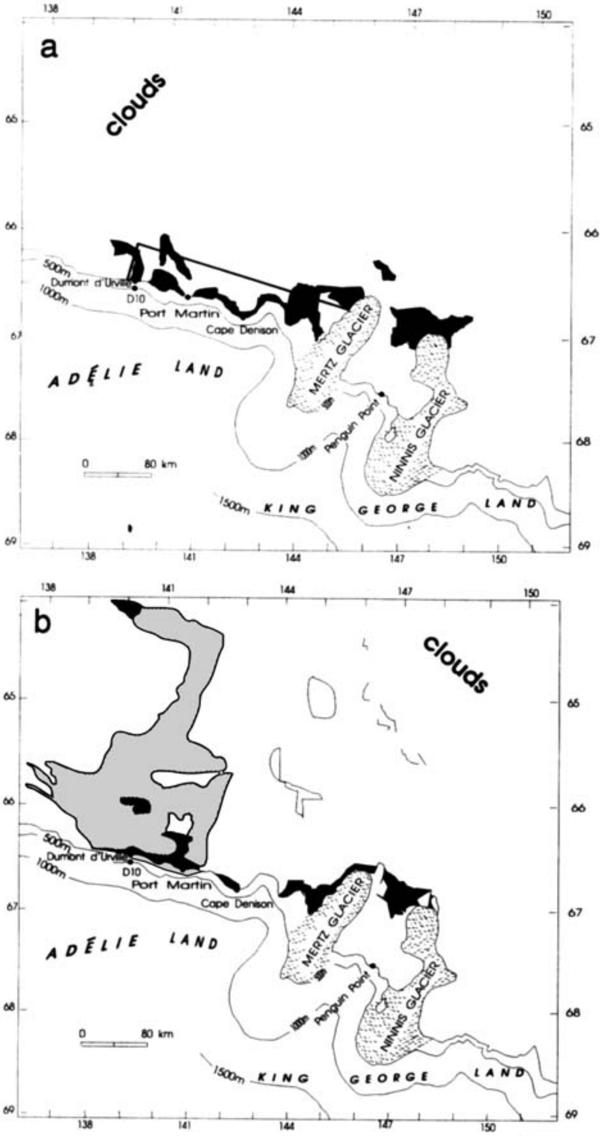
This paper focuses on a study of latent heat polynyas off the Antarctic coast in the area between 138–150°E. In order to gain a more detailed understanding of the interaction between ocean and atmosphere during the development of polynyas, local wind data are compared to satellite pictures of the coastal area for the same period of time. The interaction and mutual influence of wind strength, direction and history on one hand and polynya size, occurrence and persistence on the other hand are considered.

Results and discussion

IR-satellite observation and aerial distribution of polynyas along Adélie Coast

The study area consists of the coastal seas of Adélie Land and in part, King George Land (see frame in Fig. 1. and maps in Fig. 2a–c). The selected IR-image data set has a resolution of 2.7 km and spanned the midwinter period from 6 June to 11 July 1986. One image was obtained daily as hard copy from DMSP for all days which were partly cloudy or clear. Sixteen days fell in this category for the observational period, the remainder of the period being overcast. Eight of the 16 images were of sufficient clarity to determine accurately areas of open water and thin ice.

Fig. 1 shows an IR image of the study area on 23 June. As is common for meteorological satellites, a dark colour represents a "warm" surface, while white depicts a "cold" surface. Hence, polynyas can be discriminated by their generally darker (warmer) signature compared to land or sea ice. The schematic drawings, derived from satellite IR images, in Fig. 2a–c show the sea ice conditions in the study



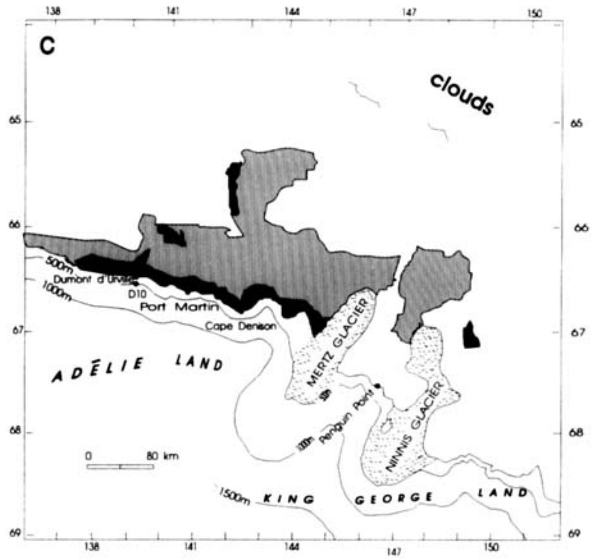


Fig. 2. Schematic representations of polynya areas. **a.** 21 June, 0048 GMT, **b.** 23 June, 0128 GMT and **c.** 30 June, 0227 GMT. Areas marked in light or dark grey represent thin ice or open water, respectively. The map shows the whole study area, Adélie coast, adjacent to Mertz and Ninnis Glacier. The framed area in Fig. 2a indicates the near coastal study area, showing also the locations of the two anemometers, one AWS at D10 and the manned station of Dumont d'Urville.

area for three specific dates. Grey or dark signature in the IR image correspond to areas marked in light or dark grey, representing thin ice or open water respectively. On 21 June the polynyas are mostly concentrated in areas near to Dumont d'Urville (Astrolabe Glacier), the Mertz and the Ninnis Glacier (Fig. 2a). The area farther offshore is mostly cloud covered. It is remarkable that the polynyas are situated in areas where large glaciers are flowing into the ocean. These glaciers act as valleys in the coastal areas of the Antarctic ice sheet, where a concentration of drainage flow is to be expected. Two days later, on 23 June (Fig. 2b), the coastal polynya near Dumont d'Urville had widened rapidly into a much bigger large scale feature, which extended significantly farther off the coastline. The IR-image of this date is shown in Fig. 1. However, the coastal polynyas near Mertz and Ninnis glaciers have diminished recognizably. The signature of the large polynya structure is either black, which indicates open water, or dark grey, which indicates thin ice. Hence, the polynya might be just about to undergo its freezing phase. Fig. 2c shows the situation on 30 June, a week later. The whole area close to the coast consists now of open water or very thin ice, especially the region along Port Martin, Cape Denison and the Mertz Glacier.

The size of polynya area was examined in the near coastal area between Dumont d'Urville and the Mertz Glacier. A 40 km boundary in the offshore direction was selected (frame in Fig. 2a), as it was believed that this area is affected most strongly by the strong offshore winds of katabatic nature. Fig. 3 shows the distribution of polynya area relative to the whole area for the dates of available pictures in the study period. Two peaks can be seen in Fig. 3: *c.* 11 June 58% of the area was ice free, which represents an area of about 2400 km². The main maximum was observed on 30 June. At this time the whole area of about 4100 km² was covered with fairly thin ice or consisted of open water.

Interaction of wind velocity and polynya development

Local wind data for the period of time were provided by two stations, Dumont d'Urville (Periard & Pettré 1992) and the AWS station D10 (see Fig. 1). Dumont d'Urville is located on an island (Ile des Petrels) about 2 km from the mainland. The anemometer is located on top of the roof of the meteorological observatory at 10 m height, whereas D10 is situated on the continent, about 5 km off the coast at an

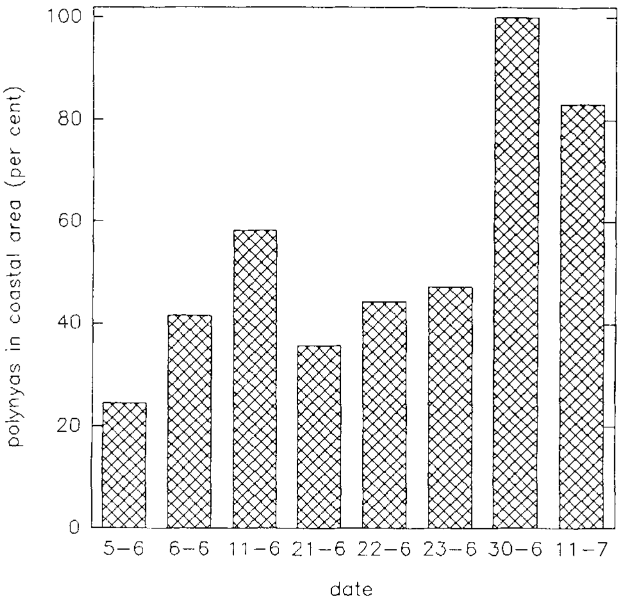


Fig. 3. Percentage distribution of polynya area of the coastal study area for the dates of available images.

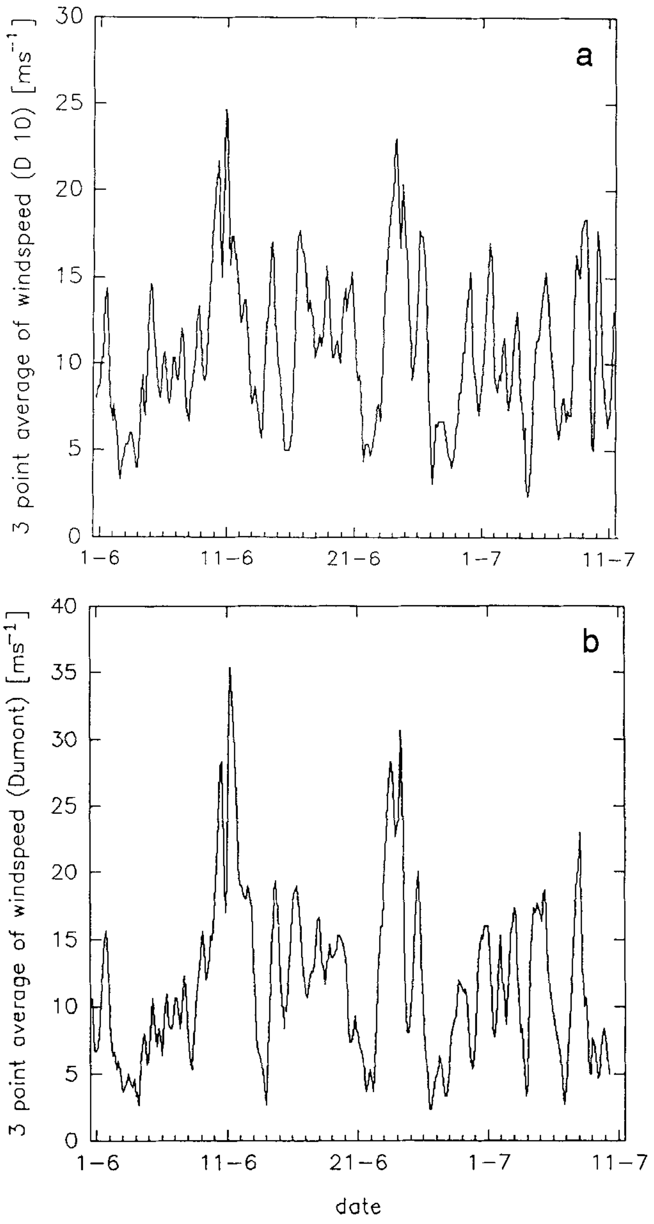


Fig. 4. Averaged 3-hourly windspeed data for the study period. **a.** D10 **b.** Dumont D'Urville.

altitude of 240 m. The wind sensor has a nominal height of 2 m. The trend in wind speed for the two stations in the period of time is shown graphically in Fig. 4a & b. It can be seen that, neglecting slight variations, the general trend of variation of the wind strength is very similar for both points. This is understandable as D10 and Dumont d'Urville are lying in line of the same katabatic outflow of wind from the continent, hence a parallel wind development is to be expected. Futhermore, by comparing Fig. 3 with Fig. 4, it can be seen that the wind speed clearly relate to the development of coastal polynya area. The maximum in wind speed on 11 June corresponds to a maximum in polynya area at that date, whereas the other maximum in wind speed around 25 June may be related to the maximum in polynya area around 30 June. Due to overcast conditions, the sea ice conditions could not be seen between 26–29 June 1986. The fact that polynya variability is strongly influenced by coastal weather systems was also stated by Cavalieri & Martin (1985) in their study of the Wilkes Land polynyas, an area not far from Dumont d'Urville. Knapp (1967) showed that cyclones substantially modulate Antarctic coastal polynyas. The interaction of strong offshore winds and open water was also detected for Terra Nova Bay, another region of strong katabatic outflow (Bromwich & Kurtz 1982). Priestley (1913) was the first to observe it for this region and Bromwich & Kurtz (1984) and Kurtz & Bromwich (1985) state that only the combination of persistent katabatic winds with the blocking action of the Drygalski Ice Tongue accounts for the persistence of the Terra Nova polynya which occupies an area of about 1000 km^2. The Mertz and Ninnis glaciers extend about 100 km north, less far than the Drygalski Ice Tongue. Hence, the sheltering effect of blocking drifting sea ice is less pronounced. Nevertheless, polynyas of substantial size do occur along the coast of Adélie Land, as we were able to show. The reason for this might be found in the fact that the katabatic winds in the Adélie Land region are the strongest in Antarctica and surpass in strength those found at Terra Nova Bay by nearly the factor of two. They extend substantially farther offshore (Zwally *et al.* 1985) than the typical distance of 10–20 km where the katabatic winds normally die out (Kurtz & Bromwich 1985). Zwally *et al.* (1985) found, for instance in his examination of Antarctic polynyas, tongues of reduced ice concentration which extended over 100 km offshore in winter in Adélie Land. This is also supported by this study which looks at a near coastal area of *c.* 40 km offshore depicting features extending even farther out in the Southern Ocean, which can be clearly seen in Fig. 2b.

Looking at the distribution of wind vectors at D10 and Dumont d'Urville showed a more southerly tendency for the station on the continent as compared to the island station. This can be explained by the fact that for the station on the continent the katabatic force is stronger, while for the island station the Coriolis force has more influence on the wind direction. Accordingly, the mean wind vectors of the two stations, which are illustrated in the wind diagrams of Figs 5 & 6 (open circles), show a more katabatic situation for D10 than for Dumont d'Urville. This is in good agreement with the fact that the katabatic wind is generated inland and blows down the continental slope towards the coast. The katabatic flow should be more pronounced and undisturbed in direction at its place of origin. The value of the directional constancy is defined as ratio of the mean wind vector length to the scalar mean wind speed. A value of 1 would mean that the wind would blow only from one direction, while the value of 0 would indicate that there is no preferred wind direction. We find values of 0.85 for Dumont d'Urville and 0.91 for D10, which are indeed very high wind directional constancies, even surpassing those of the trade winds, so well known for their directional constancy. The higher constancy value for D10 does not come as a surprise, as here the synoptic influences are less pronounced.

Figs 5 & 6 show the development of the wind vectors at both stations in relation to the mean wind vector around 11 and 25 June, which were the dates of extremely high wind speeds. Fig. 5a & b shows that as the wind speed increases during the event, it also tends to become more downslope (katabatic); this is, as expected, more pronounced for D10. The wind vectors of the second event are shown in Fig. 6a & b. As the wind suddenly grows very strong on 25 June, the wind direction becomes steadily more katabatic; again, this is better pronounced for D10 than for the island station.

We can therefore conclude that events of very high wind speed, followed by an enlarged coastal polynya area, are mainly due to an increase in katabatic strength originating from the continent rather than synoptic influences. This result is also shared by very early observations (Loewe 1972). Loewe found that the strongest winds were almost at right angles to the coast line, only slightly deviating to the left from the general direction of the slope of the ice sheet. More detailed analyses of the opening and persistence of polynyas will become possible with Synthetic Aperture Radar (SAR) data, which are able to penetrate clouds.

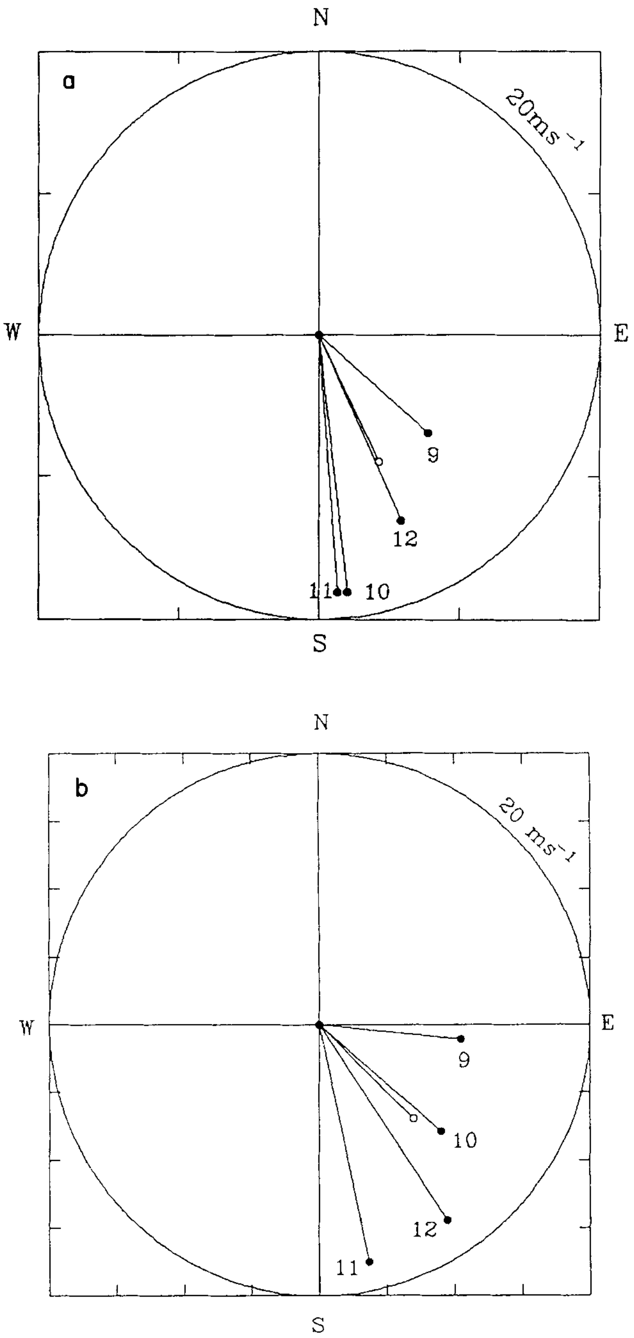


Fig. 5. Wind vector roses for the days *c.* 11 June. **a.** D10 and **b.** Dumont D'Urville. Filled circles are the origins of the coastal wind vectors. The open circle marks the origin of the mean wind vector of the study period. Daily mean vectors were derived from eight 3-hourly observations.

Broader scale influences on sea ice and local weather systems

Synoptic processes have a strong influence on the strength of the katabatic wind. While the direction of the wind is normally only slightly affected, the intensity of the katabatic wind is strongly modulated (Parish *et al.* 1993). For example, a southerly geostrophic wind, which is frequently occurring due to the pressure trough surrounding the Antarctic continent, will have a major impact on the offshore propagation of the katabatic wind, and hence on the development of coastal polynyas.

The much larger than coastal scale polynya on 23 June,

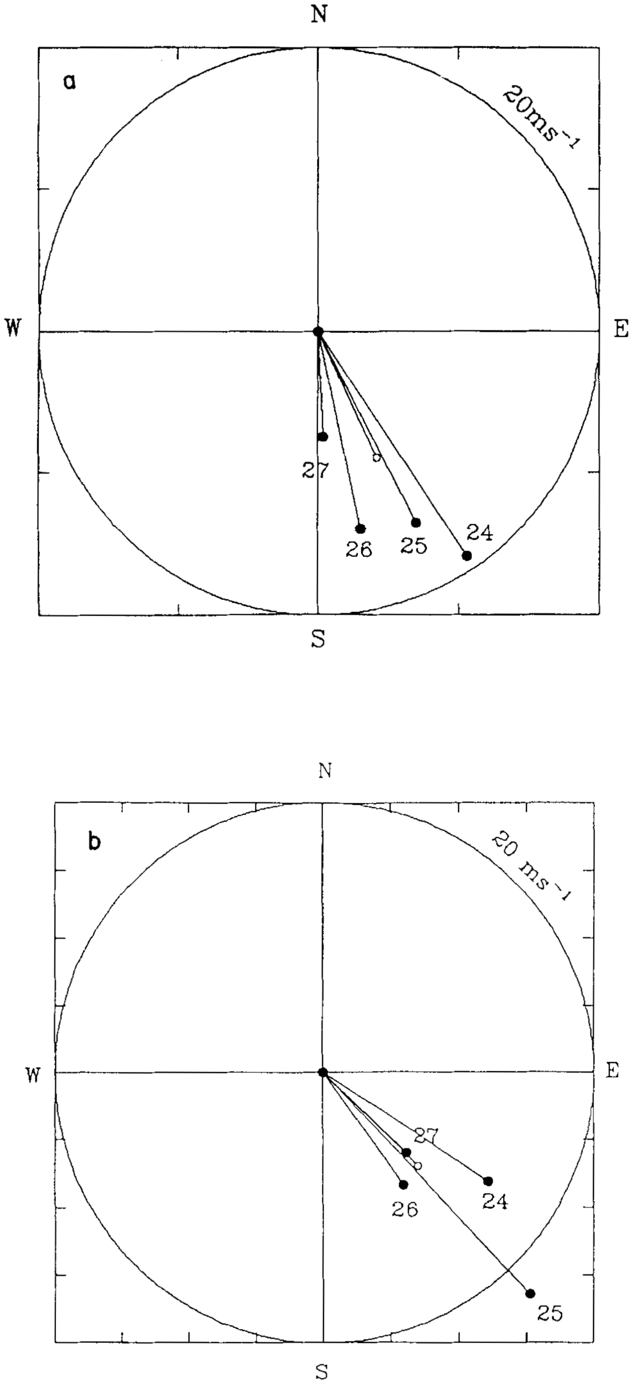


Fig. 6. Wind vector roses for the days *c.* 25 June. **a.** D10 and **b.** Dumont d'Urville. Filled circles represent the origins of the coastal wind vectors, the unfilled circle the origin of the mean wind vector. Daily mean vectors were derived from eight 3-hourly observations.

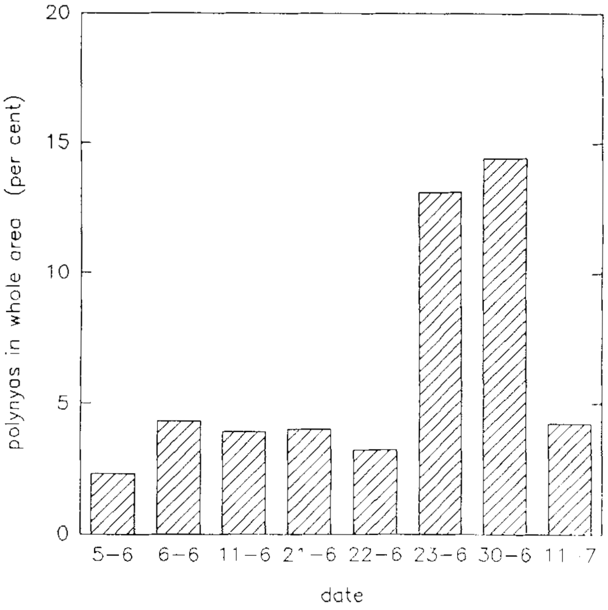


Fig. 7. Percentage polynya area of the whole study area for the dates of available images.

which is visible in Fig. 2b, cannot be explained by an extreme wind event, as can be seen from Fig. 4a & b. In fact, the local wind speed at Dumont d'Urville is especially low on this date, while the last storm occurred too long ago to be expected to still have a continued influence. Thus, the big polynya area of Fig. 2b must therefore be formed by a synoptic scale weather disturbance which is not contained in the local wind data set. We obtained from the Bureau of Meteorology, Melbourne, Australia, daily surface pressure maps for the period of interest. These maps are large scale and only the general synoptic situation can be seen. Moving cyclones are regularly occurring in the region of Dumont d'Urville (Stearns 1993). On 23 June (0h00), a cyclone was observed with a centre at 65°S 160°E, bringing a southerly airflow to the coastal regions.

Fig. 7 shows the percentage open water area distribution for the whole study area (frame in Fig.1). It shows the sudden increase in polynya area on 23 June continuing at least for a week, even allowing for possible errors in the calculation of the area due to some cloud covered regions. The graphs of local wind strength in turn indicate a sudden increase in wind speed around 25 June, shortly after the polynya formation. Hence, the question is in which way conditions in sea ice can feed back on local weather. It is generally believed (Cavalieri & Parkinson 1981, Ackley 1981) that the link from the atmosphere to sea ice is much stronger than in the opposite direction. Nevertheless, it was also pointed out (Ackley 1981) that changes in sea ice might cause anomalous atmospheric situations. The question of how the absence of sea ice can enhance local winds has been discussed by Loewe (1974). Open water or thin sea ice in winter have a much higher surface temperature than the cold Antarctic continent. The resulting large temperature gradient between the ice sheet and the coastal waters causes a thermal wind which adds to the katabatic wind, having a positive feedback on the wind velocity. This wind in turn keeps the sea open by pushing the newly formed sea ice away from the continent, thus maintaining the meridional temperature difference.

Even if there is no unambiguous answer, there is certainly evidence suggesting that the presence or absence of sea ice exerts an influence on the wind (Loewe 1974). During Mawson's stay the katabatic wind was strongest when there was no ice cover. Furthermore, the French reported the highest wind speeds at Port Martin not in midwinter, when the continent is the coldest, but in autumn (February, March and April), before the sea ice was formed (Prudhomme & Valtat 1957). Besides the thermal contrast between the cold continent and the "warm" water (land breeze), there is a bi-annual pressure variation observed for the coastal stations of Antarctica, with minima in autumn and spring. This atmospheric pressure variation is believed to be caused by radiative forcing. A strengthened synoptic pressure gradient force will also contribute to the wind maxima during these seasons.

It can be seen in Fig. 3 that the increase in coastal polynya area on 30 June, after the second extreme wind event, is much more pronounced than the one of 11 June when the peak in wind strength was the highest. A possible explanation might be that after the first wind event the general condition of the sea ice was weakened through enhanced formation of polynyas, leads, cracks etc., so that for the second wind event a smaller wind speed might be sufficient to create an even larger polynya. Thus preceding wind events might create some preconditioning of the sea ice which determines the strength of the influence of following anomalous wind events.

Conclusions

This paper describes the interaction of the katabatic wind and the formation of polynyas for an area of Antarctica, where these winds reach extraordinary velocities. Hence, polynyas can be formed at any time of the year. The paper concentrates on a relatively short time period close to midwinter. Future studies should extend the time period, especially as in the intermediate seasons (spring, autumn) the pressure trough surrounding Antarctica has its minimum (van Loon 1967, Wendler & Pook 1993). This minimum in pressure will enhance the strength of the katabatic wind, and with it the forcing on the sea ice. Future studies should focus more on the interaction of the synoptic forcing on the katabatic winds and sea ice, which should include numerical simulations. A study of the synoptic forcing on the gravity flow has previously been carried out for the coastal inland regions of Adélie Land (Parish *et al.* 1993) and should be extended to the coastal sea ice region. Presently, there are four coastal AWS stations (D 10, Port Martin, Cape Denison and Penguin Point) in operation, and some high resolution SAR imagery (20 m) has become available. Hence, the quality and quantity of the data base has increased, which makes such a future study promising.

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