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Synoptic forcing of wind and temperature in a large cirque 300 km from the coast of East Antarctica

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Abstract: Between 18 January 1988 and 3 June 1989, an automatic weather station recorded 13 different weather parameters every 3 h on a blue-ice area located in Scharffenbergbotnen, a large cirque in central Heimefrontfjella 300 km from the Weddell Sea coast. The first part of the paper reports on annual and monthly data regarding air temperature, air pressure, wind speed and wind direction, and a comparison is also made with corresponding data from the Neumayer and Halley stations. The second part deals mainly with winter (i.e. April–September) conditions in Scharffenbergbotnen. They seem, at least during 1988–89, to have been characterized by a large-scale (30–40 days) and, superimposed on the large-scale, a small-scale (3–4 days) co-variation of air temperature, air pressure and wind speed. The large-scale variation was earlier found to be synoptically forced. This paper shows that synoptic forcing exists also on smaller time scales. Pools of cold, stagnant air are regularly formed in the cirque only to be blown away by katabatic winds triggered by small variations in the synoptic pressure field. When this happens the air temperature increases by more than 20°C and the wind direction swings from east towards south-east. When low pressures dominate in the eastern part of the Weddell Sea, the katabatic winds become very strong, but weaker wind pulses also take place when the synoptic pressure gradient is directed towards the north-east. It therefore seems as if these very regular katabatic events are forced both by synoptic-scale pressure gradients and gradients due to the sloped inversion.

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Introduction

The law of supply and demand is the most important reason for katabatic air flow of a discontinuous or gusty type (Schwerdtfeger 1984). In other words, radiative cooling which dominates the Antarctic polar plateau, supplies cold, heavy air which then rushes down the fall line emptying its supply, unless the upper part of the cold air drainage area is very large. The demand, i.e. the intensity of the katabatic flow, can be modified by the synoptic pressure pattern. That happens when a cyclone passes along the coast in a track from west to east; the cyclonic movement at first hampers the outflow of cold air and later on promotes it (Ball 1960). But how far inland and upslope can the influence of these cyclones be felt? Schwerdtfeger (1984, p. 58) suggests that this southward penetration is weak and/or seldom occurs.

Although synoptic forcing of the low-level air flow is noticed at coastal stations (Shaw 1960, King 1989, Streten 1990, König-Langlo 1992), the direction of surface winds in the Antarctic interior has been found to be almost independent of the synoptic air pressure distribution. Instead, shallow inversion winds blow persistently from a direction which depends on the inclination of the topography, although due to the Coriolis effect not directly down the fall line but 30–60° to the left of it. Ball (1960) has presented a theoretical model stressing the importance of the inclination of the ice sheet surface as well as the strength of the inversion and where the downslope component of negatively buoyant air is balanced by Coriolis and friction forces. The downslope force in a stably stratified boundary layer above an inclined terrain was later named "the sloped inversion pressure gradient force" (Lettau & Schwerdtfeger 1967). Parish and Bromwich (1987) used Ball's model and the British topographic map of Antarctica (Drewry 1983) to simulate the cold air drainage over the entire continent with successful results (James 1989). A more advanced model (Parish & Bromwich 1991) gave approximately the same pattern of the Antarctic wind field, thus proving the utility of Ball's steady-state equations.

Closer to the coast, where the slope is steeper, these steady winds become more aligned with the fall line, i.e. inertial forces become dominant over the Coriolis forces (Schwerdtfeger 1970, Parish & Waight 1987). These are the true katabatic winds which are more intense but less persistent (more gusty) than the inversion winds of the interior plateau. The katabatic wind regime is also more pronounced in the sunless months when the surface cooling is at a maximum (Tauber 1960, Stearns *et al.* 1993). The distinction between inversion and katabatic winds is regarded as controversial by some researchers, but at least in a nunatak environment the distinction seems valid (see below). At the coastal station Mawson, with a mean annual wind speed of 11.1 ms^{-1}, katabatic winds are said to dominate within 100 km of the coast (Streten 1990). In some coastal areas with suitable topography katabatic winds form confluent systems and

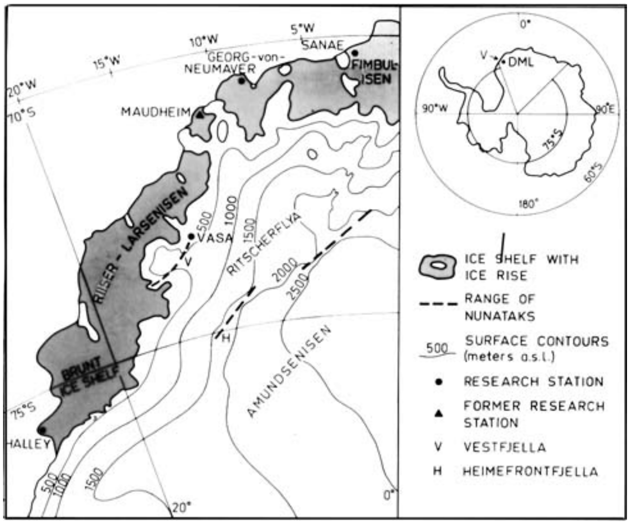

Fig. 1. Map of western Dronning Maud Land.

strong winds persist most of the time, e.g. Cape Denison with a mean annual wind speed of 19.5 ms^{-1} (Kidson 1946, Loewe 1972, Wendler 1990).

While it seems possible to predict air flow in the boundary layer on the flat polar plateau, this is less true for the mountainous nunatak areas. The wind regime near the downstream base of nunataks is characterized by frequent calms varying with strong winds. The arrival of the latter are accompanied by temperature changes which can be either positive or negative and "in all such cases the relationship to the synoptic scale pressure field is barely perceptible, if at all" (Schwerdtfeger 1984, p. 41). This paper deals with the wind and temperature regime inside Scharffenbergbotnen (SBB), a large cirque on the downstream side of Heimefrontfjella in western Dronning Maud Land (Fig. 1). Although the area is around 300 km from the Weddell Sea coast, Jonsson (1992) found that at least during the 1988 winter season the large-scale variations of temperature and wind speed were synoptically forced. This paper shows that synoptic forcing exists also on smaller time scales.

Locality and data collection

Scharffenbergbotnen (SBB)

When seen from the north-west, Heimefrontfjella is a high escarpment with ice overflowing in several places. Consequently, the ice sheet surface south-east of the range has about the same altitude as the lower passpoints of the escarpment, i.e. *c.* 2000 m a.s.l., while the ice sheet surface is *c.* 500 m lower on Ritscherflya immediately below Sivorgfjella, i.e. the central part of the nunatak range (Fig. 2). The large cirque of SBB is eroded into a promontory of the escarpment, which means divergent ice flow must prevail south-east of the cirque. The latter forms a 6 × 3 km large valley orientated NW–SE, i.e. approximately perpendicular to the trend of Heimefrontfjella and therefore more or less parallel to the regional fall line direction.

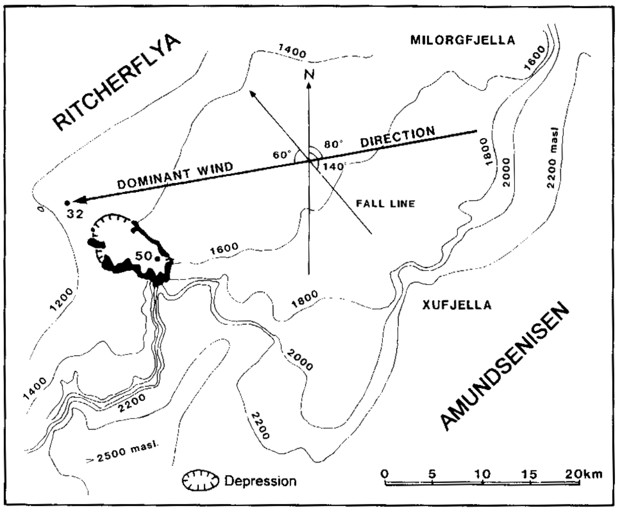

Fig. 2. Topography around the NW-facing escarpment of central Heimefrontfjella. Northeastern Sivorgfjella (with Scharffenbergbotnen marked in black) to the left and less steep terrain, where ice is flowing across Heimefrontfjella, to the right. The locations of AWS 32 and AWS 50 are marked with numbered dots. The fall line direction as well as the dominant wind direction is also marked.

The local climate inside SBB is exceptional, as shown by the fact that the regional ice flow towards north-west has been replaced by a flow *from* north-west into the valley where a depression due to sublimation has formed (Jonsson 1992). The elevation at the bottom of the depression is *c.* 1150 m a.s.l. while the western ice divide is 80–100 m higher. The headwall of the cirque is very steep and *c.* 1000 m high. Two blue-ice areas constitute approximately half the surface area of the depression, while the other half is snow-covered. Between the blue-ice areas is a large, E–W orientated snow ridge. This direction is also typical for the orientation of all wind-eroded depressions on the leesides of nunataks in the area and it is therefore believed to be the dominant annual wind direction. Wind measurements during January 1988 at a site 12 km north-west of the bottom of the Scharffenberg depression (Fig. 2) gave a steady wind from N80°E with a speed of 5.7 ms^{-1} (Jonsson 1992). A similar result was obtained for the summer season 1992–93 (Bintanja *et al.* 1993).

A model by Parish & Bromwich (1987) which shows time-averaged, near-surface, wintertime streamlines of cold air drainage over Antarctica does not include the Heimefrontfjella area. The reason for this seems to be the short length of all possible streamlines in this area, i.e. the catchment area is small. Sastrugi orientations, which are proxy indicators of resultant air flow directions, were compiled on a separate map according to which the surface air flow ought to be from ESE on the upstream side of Heimefrontfjella. These winds then seem to form a confluent system of north-easterly winds on Ritscherflya (Fig. 1).

A glaciological mass balance study was initiated in SBB in January 1988 (Jonsson *et al.* 1988) and some fieldwork was continued the following summers. An important part of this project during the first field season (18 January–18 February 1988) was the collection of meteorological data using two automatic weather stations (AWS). One (AWS 50) was operating at the bottom of the depression and the other (AWS 32) 12 km north-west of the first one (Fig. 2). Some of these meteorological data have been published together with glaciological results (Jonsson 1992).

During the austral summer of 1988 the local climate of the basin was found to be warmer, less humid, and above all, more gusty than that on Ritscherflya. A clear relationship between ablation rate, dominant wind direction and topography was also recorded (a föhn effect). Mass balance measurements showed a maximum net ablation of 22 cm ice by sublimation for the 1988–89 balance year, but only half as much for the succeeding year. The difference was most likely to be due to a higher accumulation during the second year.

Data collection

AWS 50 is an Aanderaa 2700 powered by solar cells with a lithium battery as a back-up. On and off since January 1988 this AWS has recorded weather data at the bottom of the Scharffenberg blue-ice area (74°35'S; 11°01'W) and with its sensor arm at a nominal height of 2.7 m above the surface (i.e. the exact height has been dependent on ablation and accumulation). During the summers of 1988, 1990 and 1992 the sensors were scanned every 10 min and data stored in the AWS 50. In 1988 the AWS 50 was converted into a system for satellite transmission of weather data on 11 February. From that date the Aanderaa sensors were scanned by an ARGOS sampler every three hours (GMT), using energy from batteries loaded by either solar cells or a wind generator, while the transmission of the 3-hourly data took place every minute. As a rule each set of 3-hourly values were received three times by the satellite. Still, missing and incorrect data can occur anyway and, as stressed by Stearns *et al.* (1993), sometimes for unknown reasons. The transmission from SBB lasted for over a year until it finally stopped on 4 June 1989, due to failure of the wind generator. Except for a period between 24 February and 11 March 1988, most data were correctly received over the ARGOS system.

During the ARGOS period non-ventilated sensors on the sensor arm were recording wind speed, wind gust, wind direction, air temperature, relative humidity, incoming and reflected radiation and net radiation. A sensor recording air pressure was mounted inside the electronics enclosure. Moreover, ice temperature was recorded via four thermistors set at depths between 20 and 100 cm in the blue-ice. This paper deals mainly with the continuous data set of air pressure, air temperature, wind direction and wind speed registered by AWS 50 between 12 March 1988 and 3 June 1989. The accuracy of the last three sensors is estimated to be 0.3°C, 5° and 0.2 ms^{-1}. Unfortunately, some data gaps exist for the mean (but not the maximum) wind speed values during the first half of January 1989. As this analysis deals with mean daily values, the data gaps have been filled by using the value of the maximum wind speed multiplied by an empirically obtained factor of 0.4. A test on mean wind speeds from other parts of the data set shows that maximum values become a little too high and minimum values a little too low by using this method, but that the mean value is close to the real one. Therefore the mean wind speed record is considered to be continuous as well.

Resultant wind speeds and wind directions have been compared with the sea level pressure field in the Antarctic sector between 70°W and 20°E as seen on daily (GMT 00) synoptic maps drawn by the UK Meteorological Office. These maps have been supplied by the British Antarctic Survey for the period 21 March–1 October 1988. Sea level isobars on these maps have also been calculated for the interior areas of Antarctica. Because few stations exist in the interior, and for other reasons, Schwerdtfeger (1984) is critical of this technique; in particular he is critical about data for areas higher than 2500 m a.s.l. In this paper such uncertain pressure data had to be used for minor continental areas east of SBB along 75°S.

As a result of discussions between the author and Professor Oerlemans at the Utrecht University, Dutch scientists carried out a detailed meteorological experiment in SBB during the austral summer of 1992–93, part of which included a study of the surface energy balance of the snow and blue ice areas (Bintanja & van den Broeke 1994, 1995). The annual cycle of the surface energy balance of the blue-ice at SBB 1988–89 will be discussed in a forthcoming paper by Bintanja, Jonsson and Knap.

Results and discussion

Annual data and mean monthly variation

Calculations of mean annual values of air temperature, air pressure and mean wind speed for the period April 1988–March 1989 gave -18.7°C, 878 hPa and 4.3 ms^{-1} respectively.

The monthly changes in temperatures at SBB (Fig. 3) showed an almost linear decrease between January and September followed by a very rapid increase during October and November to the summer maximum in December and January. A small secondary maximum appeared in June, something which is common in Antarctic temperature records (Goudie 1985, Glasby 1990). A similar result for June 1988 was also recorded at Neumayer station (König-Langlo 1992; also in Fig. 3) but not at Halley station (J.C. King, personal communication 1990). See Fig. 1 for the location of these two stations. The monthly temperature range, which at the Neumayer station never passed 8°C during 1988 or 1989, was, of course, much larger at the more continental SBB site.

If monthly temperature data for Halley 1988 (J.C. King,

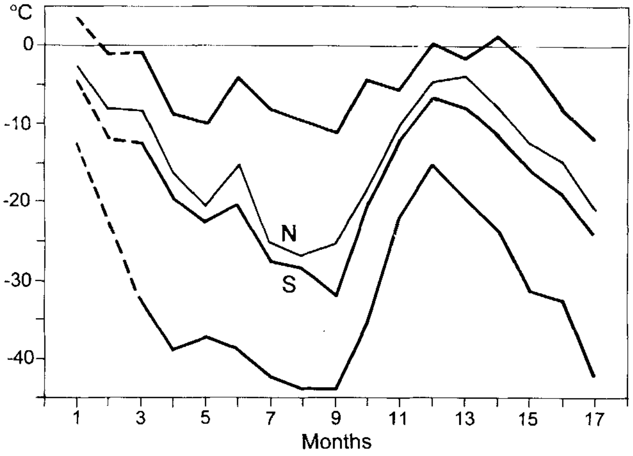

Fig. 3. Mean (S), maximum and minimum air temperatures for Scharffenbergbotnen January 1988–May 1989. Data gaps exist for January–March 1988 (dashed). For comparison the mean air temperature at the Neumayer station for the same period is shown (N).

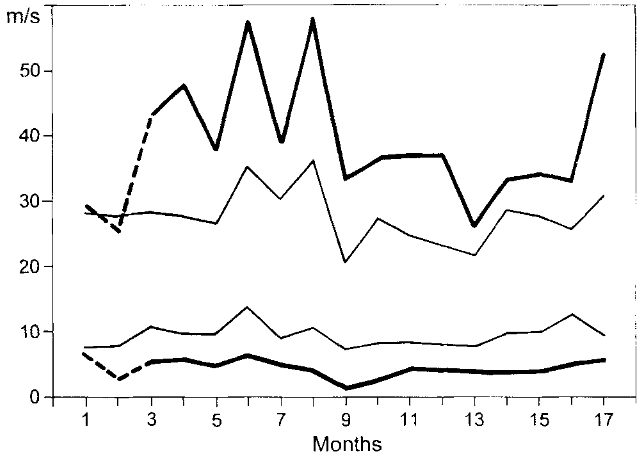

Fig. 4. Mean and maximum monthly wind speeds at the Scharffenberg depression (thick lines) and the Neumayer station (thin lines), January 1988–March 1989. Data gaps exist for January–March 1988, in the record from Scharffenbergbotnen (dashed).

personal communication 1990) are compared with mean values for 1956–82 for the same station (Kirk & Speth 1984), it seems as if 1988 can be considered a normal year. Therefore, it was most likely a normal year at SBB also. The monthly variation of temperature at SBB in 1988–89 is very similar to the mean (1956–82) monthly variation at Halley, although the latter station is located *c.* 1100 m lower (but also one degree south). Mean annual temperature at Halley is -18.5°C (Schwerdtfeger 1984), while the annual temperature at SBB for 1988–89 was -18.7°C. The relatively warm climate in the Scharffenberg depression in relation to that at Halley seems to extend also to the general area below the Heimefrontfjella escarpment judging from a 10 m firn temperature taken by Isaksson & Karlén (1994). Around 30 km north-west of AWS 50 and at an elevation of 1200 m a.s.l. they found this proxy for the mean annual temperature to be be -20.0°C. Their data also show a very low lapse rate (0.3°C/100m) between the edge of the Riiser-Larsen Ice Shelf and the above-mentioned site.

Surface winds were registered from all directions, but most winds from a coastal quadrant (north-west or south-west winds) were very weak and south-west winds were rare. If daily resultant wind directions are calculated (Liljequist 1970, p. 440) for the year 1 April 1988 to 31 March 1989, only one day had daily wind speeds >1 ms^{-1} blowing from the south-west and only 4.4% of the days had winds of this magnitude blowing from the north-west. Calm or very weak winds (<1 ms^{-1}) were typical during 36% of the time, while south-easterly winds >1 ms^{-1} dominated 46% of the days. In particular, the resultant wind direction was from the south-east for 88 of the 93 days with strong daily winds (>5 ms^{-1}).

Between April and July 1988, and April and May 1989, more than 10 days each month had very strong winds (daily resultant wind speeds >8 ms^{-1}) and these winds always came from directions between east and south-east. Maximum wind gusts were observed on 9 June (57 ms^{-1}) and 18 August (58 ms^{-1}). Although high maximum wind speeds were recorded during the polar night months (Fig. 4), the monthly mean wind speeds did not differ much (4.3±1.3 ms^{-1}). Maximum and minimum mean wind speeds were recorded respectively in June (6.6 ms^{-1}) and September (1.7 ms^{-1}). The frequency of calm weather was particularly high during September, when the daily mean wind speed was <1 ms^{-1} during 60% and <2 ms^{-1} during 73% of the days. It is also interesting to note that the summer period has relatively few days with weak winds (resultant winds <1 ms^{-1}). This is also the main period when winds of moderate magnitude reach SBB from the north-west.

Months which gave extreme wind speed values at SBB also have extreme values at the coastal station, Neumayer (König-Langlo 1992). But at Neumayer maximum wind speeds which varied between 20 and 35 ms^{-1} during the whole period were normally much lower than those at SBB. If, on the other hand, the annual mean wind speed for Neumayer is calculated for the same months as for SBB, the results show 9.4 ms^{-1} with extreme values for June (13.9 ms^{-1}) and September (7.5 ms^{-1}). Therefore, no month at SBB was, at on average, as windy as the least windy month at Neumayer.

The monthly values of air pressure at SBB 1988–89 varied in an almost inverted fashion to that normal at Halley (Fig. 5) and other coastal stations. Monthly air pressures equal to or higher than the annual mean (878 hPa) existed between April and October 1988 (and returned during April and May 1989) with a maximum value recorded during September, while the air pressure was low during summer. The monthly range of air pressure was very large during winter 1988 (March–October) at SBB compared with conditions at a coastal station like Neumayer (König-Langlo 1992), but this

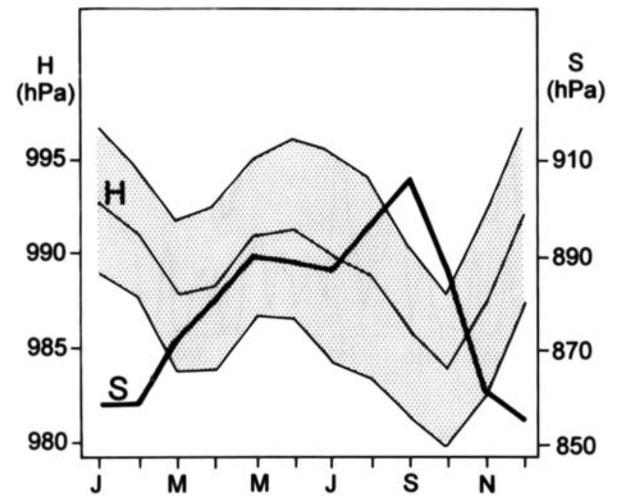

Fig. 5. Mean monthly air pressure at Scharffenbergbotnen (S) April 1988–March 1989 compared with the mean monthly air pressure at the Halley station (H) 1956–1982. The shaded area shows the deviation around the Halley mean value (± 1 s.d.). The 3 monthly values from 1989 at Scharffenbergbotnen (January–March) have been plotted ahead of those from 1988.

difference disappeared during the summer months (Fig. 6). The variability of minimum pressures was small and similar at the two stations while that of the maximum pressures was not. Indeed, at Neumayer station the maximum pressures had very little variation between different months, something which contrasts with the large seasonal difference in the Scharffenberg depression. The difference in mean minimum pressures at the two stations corresponds to an approximately correct altitude difference, while this is true only during December 1988 and January 1989 when the difference in maximum pressures is studied. The reason for the large range during winter at SBB was explained by Jonsson (1992) as connected to the periodic formation of cold air pools.

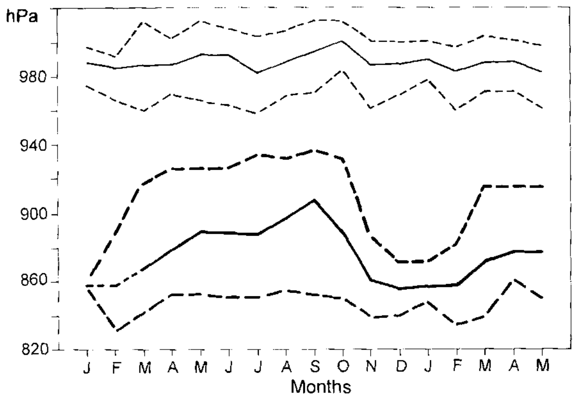

Fig. 6. Mean, maximum and minimum monthly air pressure at the Scharffenberg depression (lower thick lines) and at the Neumayer station (upper thin lines), January 1988–May 1989. Data gaps exist in the record from Scharffenbergbotnen for January–March 1988.

The annual range of monthly mean air pressures at SBB is *c.* 50 hPa compared with 10 hPa at Halley. One reason for this could be that the pressure sensor was temperature sensitive, which could possibly explain high readings during cold periods. This seems unlikely as the sensor was bought for this experiment in Dronning Maud Land, and was calibrated before and tested after the experiment (at the Aanderaa factory) with a normal result. The test after the observation period was carried out at temperatures down to -37°C and as some of the large-scale, periodic variations took place at higher temperatures they must be real. Temperatures below -40°C were particularly frequent during the first half of September and the pressure graph seems to indicate that the sensor reacted more slowly at these low temperatures, but still in phase with the other sensors.

On the other hand the anomalously high pressure in the cirque can hardly result only from the excess hydrostatic pressure of cold air trapped in the cirque. A simple hydrostatic calculation for a 200 m thick cold pool, assuming that the cold air is 20°C cooler than the ambient air throughout this depth, gives a surface pressure in the cold pool an order of magnitude smaller than the anomaly that must be explained. As therefore the hydrostatic explanation can only explain a small part of the excess pressure in the cirque this leaves mesoscale dynamical effects as the only reasonable explanation; that is, the flow of stably-stratified air around the surrounding topography must generate a mesoscale pressure field.

Periodic variations

Jonsson (1992) showed that the air pressure at SBB during winter 1988 varied with a distinct periodicity of 30–40 days. He also noticed that this variation could be seen in pressure data from the Halley station but was not so evident. This variation was found to be synoptically forced but amplified by the special topography of the Scharffenberg basin. Whenever major cyclones (<960 hPa) passed the eastern part of the Weddell Sea area south of 60°S low pressure periods with high temperature and strong winds characterized weather at SBB (Fig. 7). Extreme values were reached when the cyclones centred at 65°S, 15–25°W (Fig. 8). These very regular occasions were separated by seven high pressure events when low temperatures and generally calm weather dominated in the Weddell Sea sector. The larger-scale periodic variation disappeared at the beginning of October 1988 but reappeared at the beginning of March 1989. Superimposed on the larger-scale, periodic variation was a smaller-scale of the same parameters which between April and August 1988, had a period of 3–4 days. Jonsson (1992) showed that the cessation of strong winds led to the formation of pools of cold, stagnant air and a high air pressure in the Scharffenberg basin. These cold air pools were regularly blown away by katabatic winds.

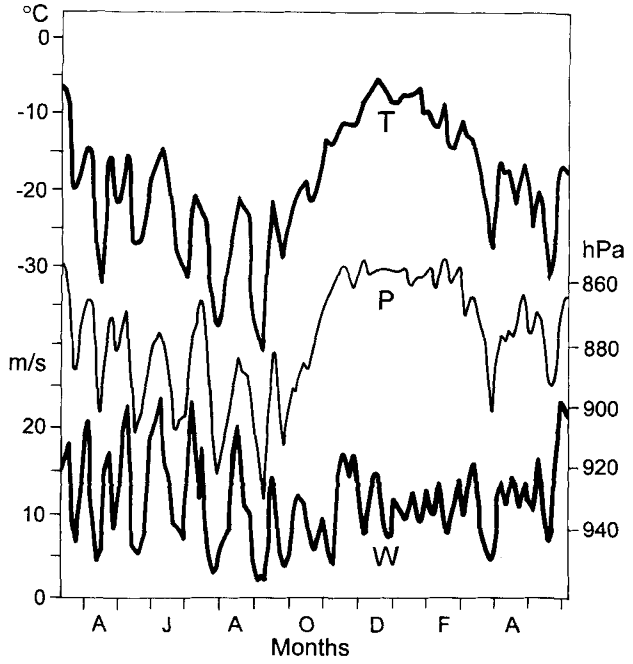

Fig. 7. Weekly running means of air temperature (T), maximum wind speed (W) and air pressure (P) between 12 March 1988 and 3 June 1989. Notice that the latter parameter has an inverted scale.

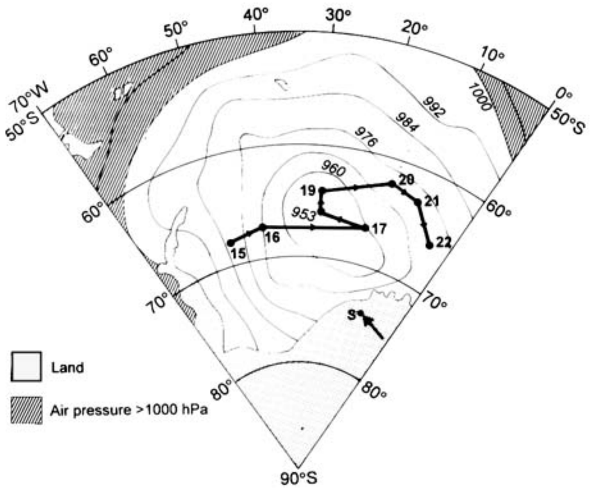

Fig. 8. Synoptic map of the Weddell Sea area 18 August 1988. A cyclone with a minimum pressure of 953 hPa gave a mean wind speed of 18.8 ms^{-1} at Scharffenbergbotnen (S) with wind gusts reaching 58 ms^{-1}, the highest value for the whole period. The resultant wind direction at Scharffenbergbotnen (118°) is drawn as well as the day by day (15–22 August) track of the cyclone causing the high wind speeds.

If daily running means of air temperature, air pressure (inverted scale) and maximum wind speed are plotted for the coldest part of winter 1988, a detailed illustration of the smaller-scale variations appears. As an example (Fig. 9) a graph displaying two 30–40 days periods and *c.* 20 short periods is shown. Because the three studied parameters co-vary it is possible to fill in or exclude maxima (minima) in one graph by using the other two. For example on day 145 a maximum is clear on the pressure graph where it is expected to be, while the temperature graph has a plateau and the wind graph shows nothing. One exception to this regular, smaller-scale variation took place during the first half of September. This was an extreme period in SBB with hardly any wind gusts, high pressure (Fig. 14b) and the lowest temperatures of 1988. Then the 3–4 day variation disappeared completely, although it reappeared later that month and then could be followed in all three types of graphs until mid-November. The following year the same 3–4 days rhythm started to show again at the beginning of March and can be followed to the end of the data set. The graphs of individual katabatic events usually show up as rapidly rising limbs, short-lived peaks and rapidly declining limbs. Sometimes, and more frequently for the air temperature graph, the declining limb has the same shape as a recession curve for a storm hydrograph.

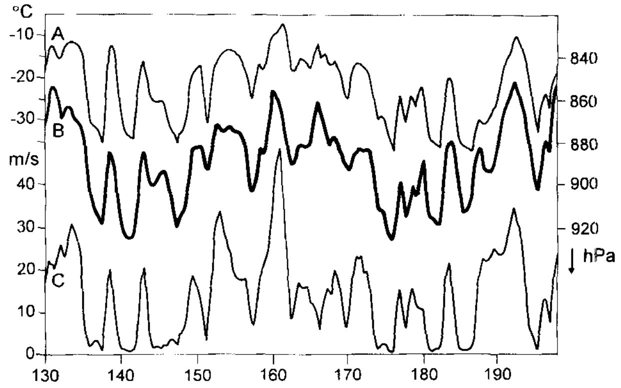

Fig. 9. Daily running means of air temperature (A), air pressure (B) and maximum wind speed (C) at Scharffenbergbotnen 9 May–15 July 1988, (68 days).

Wind direction and katabatic events

Directional constancy is defined by the ratio between the speed of the resultant wind vector and the mean wind (Schwerdtfeger 1984, p. 42). A value of exactly one unit indicates that all measurements have shown the same direction although the wind speed might have varied. Due to the generally weak winds during some months, the average directional constancy was *c.* 0.80, which is a rather low value for a site at some distance from the Antarctic coast (Schwerdtfeger 1984). The range was between 0.67 in October 1988, and 0.93 in April 1989. If only days with daily resultant winds >8 ms^{-1} are used, the directional constancy increases to 0.94, a value more typical of the outer parts of the Antarctic polar plateau.

As all strong winds come from the same general direction, perhaps an even higher directional constancy could have been expected for the windy days. One reason this is not so is shown by graphs of the resultant wind vector during windy periods. The windiest period in the data set is around 18 August when a maximum wind speed of 58 ms^{-1} was recorded. The daily resultant wind vectors between 15 and 22 August show a rapid increase in wind speed from 15–17 August, while the daily resultant wind direction swings from west to north-east (48°) on 16 August and on to south-east (122°) or close to the fall-line direction (Fig. 2) on 17 August. On 18 August the resultant wind stays much the same and then the wind swings back again, although in a more complex way. This is well illustrated by the trace of running daily means of the resultant wind vector (Fig. 10).

Each mean is based on eight consecutive values and plotted on the time of the first value. This means for instance that on GMT 00 is plotted the mean of the eight values for that particular day (points on the curve in Fig. 10), while the following seven means are based on eight consecutive values from two days. The wind vector is always orientated from a point on the curve towards the origin.

This deflection of the winds from the east to the south-east is clearly seen in monthly graphs of the same type. June 1988 (Fig. 11a), the windiest month, is of course the best example, but it can also be seen in the less windy summer months as in December 1988 (Fig. 11b). It is also important to note that 1988 is no exception; e.g. the graph from May 1988, is very similar to the graph from May 1989.

If the resultant wind vector is dissolved into its meridional (north–south) and zonal (east–west) components, the analysis can be carried on even further (Fig. 12). To begin with, it is clear (without use of statistical methods) that during winter the regular 3–4 days periodicity between katabatic events is seen both for the zonal as well as the meridional component. The best example was recorded during August 1988 for which a 3.5 day periodicity is very obvious (Fig. 12a). The increase in wind speed seems to start with an increase of the zonal component (i.e. an increase of winds from the east) and after a while the wind starts to swing to the south (a positive increase of the meridional component). The swing back to weaker winds sometimes takes place at the same time for the zonal and meridional component. In some cases it seems as if the katabatic event starts with a negative pulse of the meridional component, i.e. more north-easterly winds to start with, e.g. 16 August 1988 (compare Fig. 12a with Fig. 10), and 4 May 1989 (Fig. 12b).

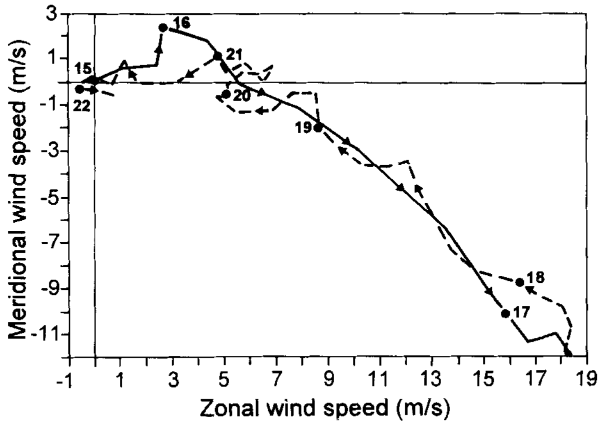

Fig. 10. Track of the daily running means of the resultant wind vectors at Scharffenbergbotnen 15–22 August 1988. The wind vector is always orientated from a point on the curve towards the origin.

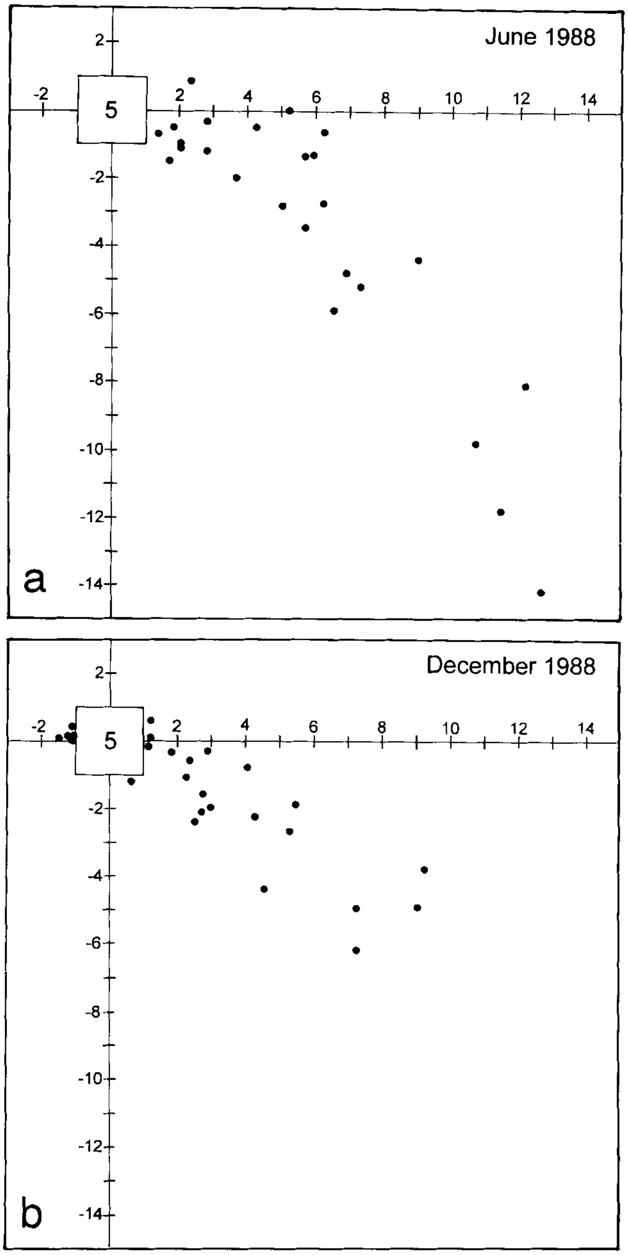

Fig. 11. Daily resultant wind vectors for two different months at Scharffenbergbotnen. See text and Fig. 10 for explanation. The square at the centre gives the number of days with very weak winds. **a.** June 1988. **b.** December 1988.

Although episodes with strong easterly winds, which are deflected towards the south-east when the wind speed increases, do take place during the summer and with a

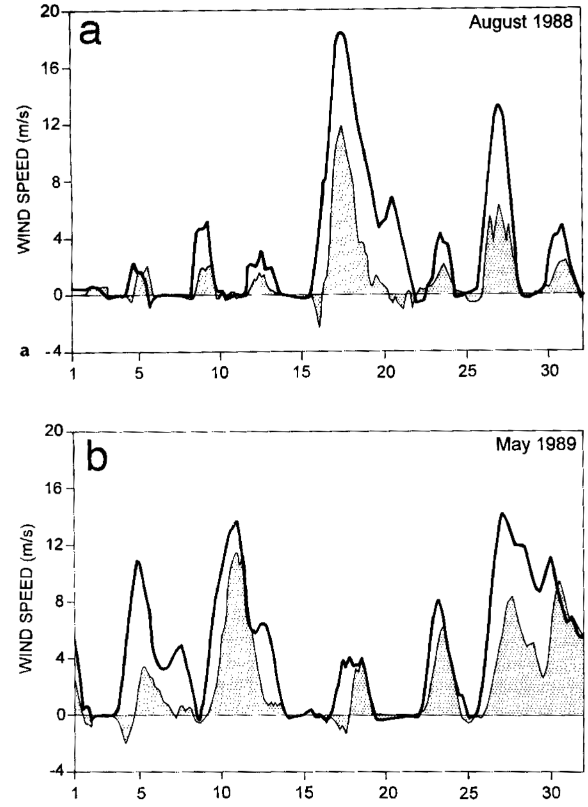

Fig. 12. Zonal and meridional wind speeds (daily running means) for different months at Scharffenbergbotnen. A positive increase of the zonal wind speed means an increase of easterly winds. A positive increase of the meridional wind speed means an increase of southerly winds. **a.** August 1988. **b.** May 1989.

frequency that approaches that typical for the winter (nine events per month), but they occur much less regularly. Their origin is probably more complex than that of the winter ones, depending on, among other things, the ice-free conditions in the Weddell Sea which changes the horizontal temperature gradient (Pettré *et al.* 1993). Another difference between summer and winter, but in this case specific for a blue-ice area like SBB, is the importance of weak winds from the north-west during summer (Fig. 11b), i.e. along the local fall line inside the cirque. The cause of moderate winds from the north-west during summer was explained by Bintanja & van den Broeke (1994) in their study of the surface energy balance in SBB. In summer, when the katabatic wind regime as a whole is weaker, a strictly local circulation is sometimes induced in the basin of SBB. This is caused by adiabatically warmed air that rises from the blue-ice areas followed by inflow of colder surface air from the north-west. More specifically, this is due to the low albedo of the blue-ice (0.56) and the sheltered character of the basin which causes upwardly moving fluxes of long wave radiation as well as turbulent fluxes to heat the air.

Synoptic forcing of katabatic events

The strong cyclones which approached the area north-west of Neumayer station between May and September 1988, always gave a strong signal in the wind record at SBB. This signal is particularly well displayed when wind data is plotted with separate graphs for zonal and meridional components. The katabatic wind pulses associated with cyclones in the eastern part of the Weddell Sea give long-lasting maxima for the zonal component with wind speeds (daily running means) normally between 10 and 18 ms^{-1}. Zonal wind pulses for the other katabatic events are shorter and more regular and with wind speeds below 10 ms^{-1}; normally the zonal wind speeds are between 3 and 8 ms^{-1}. Some interesting parts of this data set are discussed below.

Daily sea level pressure in the Weddell Sea sector has been analysed in order to determine different cyclone tracks, e.g. the track of the cyclone that gave the strongest katabatic winds at SBB (Fig. 8). On 15 August, a cyclone passed across the Antarctic Peninsula but the minimum pressure was still relatively high (976 hPa) and as the cyclonic centre was rather distant, weak winds dominated at SBB. The following day the cyclone had developed a somewhat lower minimum pressure and was closer as well. A steady wind from the north-east (directional constancy 0.85) blew approximately parallel to the isobars at SBB. During the next three days minimum pressures below 960 hPa characterized the cyclone and particularly during the first two days very strong gusts were measured at SBB (Fig. 10). The directional constancy of the wind was very high (0.98). The wind direction turned to *c.* 120°, which meant it was close to the fall-line direction but also more aligned to the pressure gradient direction than the geostrophic one; the latter was typical during 16 and 20 August though. On 22 August weak winds dominated again.

On 26 and 27 August high winds (maximum wind speed 44 ms^{-1}) were again measured at SBB (Fig. 12a); this time caused by a cyclone originating west of South Georgia and then moving south-east. The cyclone had three days with minimum pressures below 960 hPa, but as the track was further away, the effect was smaller at SBB than it was for the preceding cyclone. The wind direction at SBB approached the pressure gradient direction.

Between 1 May and 31 July 1988, six different cyclones came close to the coast around Neumayer station and thereby caused six zonal wind speed maxima (daily running means) >12 ms^{-1} at SBB. All the other maxima during this period have zonal wind speeds <10 ms^{-1}, and seem to represent katabatic pulses not related to a specific cyclone; at least not close to the north-eastern Weddell Sea coast (see below). Wind directions at SBB were during the first-mentioned six cases approaching the synoptic pressure gradient direction, while the direction was more geostrophic in the other cases. Unfortunately, the author has only had access to synoptic maps up to 1 October 1988, which perhaps makes an interpretation of a graph from the windy month of May 1989 speculative (Fig. 12b). Still, the katabatic signals seem to be the same as for those periods already described, and therefore it can be suggested that three cyclones came close enough to the north-eastern Weddell Sea coast to enhance the speed of katabatic winds at SBB.

During the first half of August 1988 four small katabatic events took place at SBB (Fig. 12a). The synoptic maps from this period show that high pressure dominated over the Weddell Sea while low pressure was typical in the coastal areas of the Haakon VII Sea (area around the Greenwich Meridian). Similar pressure conditions also characterized the other periods with zonal wind pulses below 10 ms^{-1} like 22–25 August 1988 (Fig. 12a). During all these periods with small katabatic events the synoptic pressure gradient in western Dronning Maud Land was directed towards the Haakon VII Sea (Fig. 13a) or coastal areas south of it (Fig. 13b), while geostrophic winds above SBB became more south-easterly. In the latter case, a low pressure was often found centred at 75°S, 0–10°E. Kottmeier (1986), who studied wind and temperature conditions at Neumayer station during the 1983 winter season, found that 23% of the daily resultant winds came from the south-west with a mean speed of 8 ms^{-1}. These winds were explained as being due to low pressures south of the station.

King (1989) described how, in 1985, the air flow at Halley on the Brunt Ice Shelf (Fig. 1) was dominated by easterly surface winds, which appeared to be forced both by synoptic-scale pressure gradients and the pressure gradients due to the sloped inversion. The latter topographic effect always gave a wind component from the east at the surface, while the former either strengthened or weakened the wind speed due to the direction of the geostrophic winds at 2000 m elevation. These were predominantly either north-easterly winds connected with passing cyclones or south-westerly winds normally connected with a high pressure area over the Weddell Sea. He also mentioned that, on some occasions, the south-westerly geostrophic winds were associated with a low pressure area centred at 75°S, 0°W. This picture seems to fit well with the data from SBB.

The importance of the reversal of the pressure gradient force that causes sudden decay of katabatic winds in the coastal zone has been stressed in modelling efforts (Gallée & Schayes 1992). No clear connection between reversed synoptic pressure gradient alone and calm weather can be detected in the SBB data, as, at regular occasions, katabatic wind pulses were able to penetrate towards the coast more or less in opposition to the synoptic-scale pressure gradient. Therefore it might seem as if the wind pulses were caused by the sloped inversion pressure gradient alone, when the supply of cold air was large enough.

But in many instances the low pressure cell in the Haakon VII Sea must have been a forcing factor as well; at least when it was centred close to the coast as it was in the second half of May 1988 (Fig. 13a).

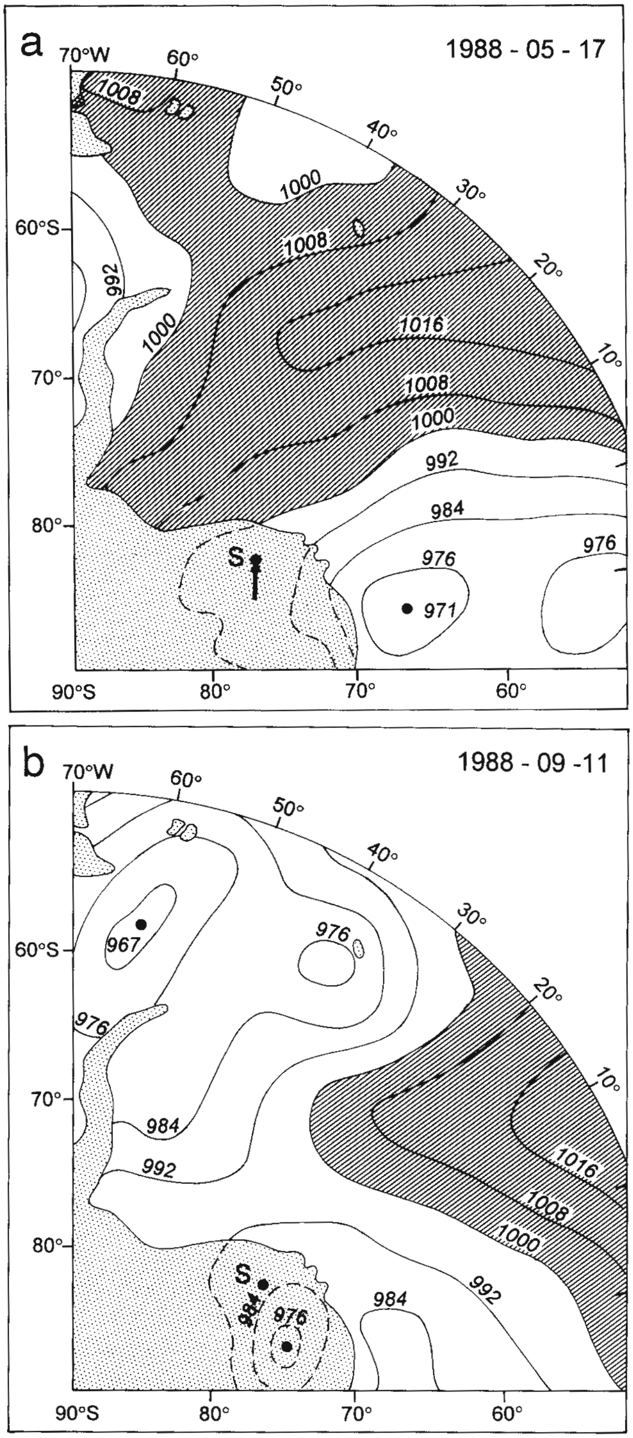

Fig. 13. Daily synoptic maps of the Weddell Sea area. See legend of Fig. 8. **a.** 17 May 1988. Mean wind speed at Scharffenbergbotnen was 4.2 ms^{-1} and the daily resultant wind direction 122°. **b.** 11 September 1988. Mean wind speed at Scharffenbergbotnen was 0.4 ms^{-1}.

That synoptic forcing, at least in part, is also active during high pressure periods in the Weddell Sea sector can be demonstrated by taking spot values from the daily synoptic maps. Spot values of mean sea level pressure at 70°S, 10°W, i.e. from the border area between the Weddell Sea and the

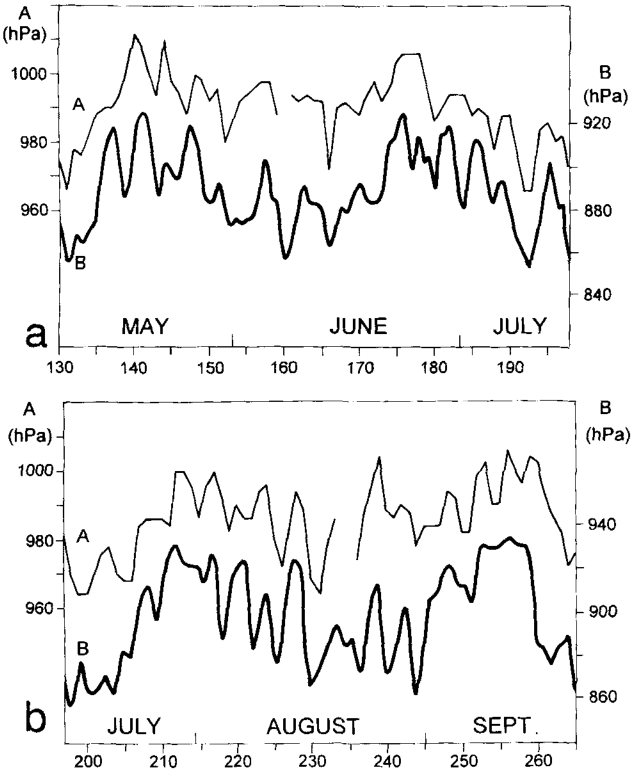

Fig. 14. Daily point values of air pressure at 70°S, 10°W taken from synoptic maps (A) compared with daily running means (8 points) of air pressure at Scharffenbergbotnen (B). **a.** *9 May–15 July 1988.* **b.** *15 July–20 September 1988.*

Haakon VII Sea sectors — have been chosen and compared with the daily running mean pressure values from SBB (Fig. 14). As the latter values are anti-correlated with the wind speed values (Fig. 9), Fig. 14 indirectly shows that the wind speed in SBB varies in phase with inverted pressure data from the northeastern part of the Weddell Sea. A striking resemblance is seen and this resemblance is not only valid for the windy periods in late August, but also for the much less windy periods in early August; in fact it seems to be valid for the whole winter period but the first part of September (Fig. 14b).

The first half of September is exceptional, with hardly any winds at SBB. The synoptic maps give a pressure gradient directed from the Weddell Sea towards a low pressure area in the interior of the Dronning Maud Land east of SBB, but there is hardly any high pressure in the Weddell Sea. The synoptic picture is therefore different from that of the other weak wind periods of winter 1988, as low, or fairly low, pressure dominates in the Weddell Sea as well as the southern parts of the Haakon VII Sea. An unusual September 1988 in western Dronning Maud Land, or at least markedly different from earlier years, was also described by BAS scientists studying the stratospheric circulation over Antarctica (NERC 1990). It is also worth remembering that this month gave the lowest monthly maximum and mean wind speeds not only at SBB but also at Neumayer (Fig. 4).

Conclusions

Fortuin & Oerlemans (1990) has shown that the lapse rate in the "escarpment region" (200–1500 m a.s.l.) normally is 0.5°C 100 m^{-1}. As 10 m firn core temperatures from Riiser-Larsenisen and Ritscherflya show (Isaksson & Karlén 1994), the lapse rate to central Heimefrontfjella is much less. The temperature climate north-west of Sivorgfjella is therefore unusually warm for its altitude. This is also shown by the 1988–89 mean air temperature at SBB which is close to that of nearby coastal stations.

Monthly temperatures and wind speeds at SBB during 1988 and the first half of 1989 varied in phase with those measured at Neumayer station, but were lower and with much greater variability; the mean wind speed at SBB (4.3 ms^{-1}) was only half of that recorded at Neumayer. As the latter station has a mean wind speed typical for stations with ordinary katabatic winds (Schwerdtfeger 1984), the value for SBB is very low. On the other hand, monthly maximum wind speeds were normally 10–20 ms^{-1} higher at SBB than at Neumayer, but the two graphs follow each other as both stations were affected by the same large cyclones.

Monthly minimum air pressure variability at SBB was similar to that at Neumayer station in contrast to those of mean and maximum air pressure. The air pressure range at the two stations was similar during the austral summer, but much greater during the winter. In fact, winter conditions at SBB seem to be very unusual with periodic large-scale (30–40 days) and small-scale (3–4 days) co-variation of air temperature, wind speed and air pressure. The high pressure events are on both scales connected with the formation of stagnant air inside SBB, but also due to mesoscale dynamic effects. Although pools of stagnant air form during summer nights (Bintanja *et al.* 1993), longer periods with these conditions are probably typical for the winter months.

The large-scale periodic variations were very obvious up to the beginning of October, when the seasonal increase of air temperature started and therefore the intensity of the katabatic wind regime decreased (Tauber 1960). The small-scale periodic variation could be followed to mid-November, when summer temperatures had been reached and unstable conditions could form during daytime inside SBB (Bintanja & van den Broeke 1994). Thus, periods with weaker katabatic winds upslope Sivorgfjella which during winter were characterized by stagnant air inside SBB, were, at least on a daily basis, often characterized by north-westerly winds during summer. For instance during December 1988, and January 1989, five days each month had resultant winds >1 ms^{-1} (but <2.5 ms^{-1}) from the north-west sector.

Compared with normal conditions at other Antarctic research stations, the frequency of calm periods seems to have been very high (Schwerdtfeger 1984). This can be exemplified by the fact that exactly 50% of the days had wind speeds <2 ms^{-1}; 36% if only days with <1 ms^{-1} are counted. During these calm periods, very cold air formed in the sheltered cirque only to be blown away when the next katabatic event started (Jonsson 1992, fig. 7). Then the temperature rapidly increased more than 20°C as the wind speed increased. This sudden warming must be due to entrainment of air from the free atmosphere into the katabatic layer (Schwerdtfeger 1984). Such an entrainment can arise either from a turbulent mixing process or from mass divergence in the katabatic stream (Parish & Waight 1987). Both these processes could be applicable for SBB, but in favour of the second and more unusual one is that this large cirque is located at a promontory of Sivorgfjella which makes it particularly hard to reach for cold (more dense) surface winds from south-east.

During the summer 1992–93 wind speeds were recorded on automatic weather stations located close to the sites of AWS 32 and 50, as well as at an altitude of 2550 m a.s.l. 3 km south-east of SBB (Bintanja *et al.* 1993, table 3). Results from these three sites show decreasing mean wind speeds (at 6 m) towards the interior (5.2, 4.9, and 4.4 ms^{-1} respectively). At the site on 2550 m which had the lowest wind speed, the wind direction varied between east and south (for wind speeds >6 ms^{-1}) with an approximate mean of south-east (R.Bintanja, personal communication). Although this record was only for a short summer period, it probably gives an idea of annual wind directions above the Sivorgfjella escarpment. This supposition is strengthened by a SPOT image from 1987-02-03, covering the high, central part of Heimefrontfjella, where snow drifts indicating dominant winds from ESE are seen on the leeside of steep slopes east of SSB.

The wind direction in and around SBB, as shown by major snowdrifts and leeside depressions below northern Sivorgfjella, point to dominant winds from N70–80°E. But similar features (on the SPOT image) below more southern parts of Sivorgfjella, indicate dominant winds parallel to the escarpment, i.e. winds from N45°E. It therefore seems as if the cold surface winds coming from the interior towards northern Sivorgfjella turn to form north-east winds below the Sivorgfjella escarpment. Apparently these winds are unaffected by the larger-scale air flow higher up, while the surface winds diverge around Sivorgfjella.

Even if easterly winds are dominant north-west of SBB, a substantial frequency of the winds recorded inside the cirque comes from more south-easterly directions and always with high wind speeds. Daily resultant winds from the south-east sector, and with speeds of 5 ms^{-1} or higher, were for instance recorded during 24% of the days between 1 April 1988 and 31 March 1989. Whenever the wind speed of easterly winds increased to >3 ms^{-1} the wind direction would start to swing towards the south-east, i.e. the regional fall line direction but also the direction of the Scharffenberg valley. This deflection of the wind was also registered during summer.

The large-scale variation (30–40 days) of temperature and winds was earlier found to be synoptically forced (Jonsson 1992). Yasunari & Kodama (1993), who studied the intraseasonal variability of the katabatic winds around Mizuho in eastern Dronning Maud Land, found that the speed of these winds varied with a period of 30–50 days. They also suggested that this periodic variation is connected with the variability of the flow regime of the middle and upper troposphere in the middle and polar latitudes of the Southern Hemisphere. In particular they found that the tropospheric polar vortex was less intense when the katabatic winds were stronger and vice verse. According to Simmonds & Law (1995), who gave support to this relationship through GCM experiments, this could imply a thermal control. As the troposheric temperature difference between the continent and surrounding areas lessens at the end of the polar night, this might explain why the 30–40 days variation seen at SBB could only be registered to the beginning of October 1988.

Besides a large-scale, synoptically forced variation of wind speed and temperature this paper has shown that synoptic forcing of katabatic winds is, at least partly, an active process in generating a small-scale variation (3–4 days). During May–August 1988, around nine katabatic events took place each month. The synoptic influence is particularly obvious when large cyclones (<960 hPa) come close to the north-eastern coast of the Weddell Sea and pull cold air from the interior of Dronning Maud Land. But on other occasions, when the main low pressure area is found in the Haakon VII Sea, katabatic events take place in SBB when the air pressure is higher in the Weddell Sea than over the ice sheet. Therefore the katabatic events have been divided into two groups.

The first group had zonal wind speeds (daily running means) >10 ms^{-1}, and occurred when large cyclones approached the area north-west of Neumayer station. The other group of katabatic wind pulses were more regular, shorter in duration and had maximum zonal wind speeds reaching between 6 and 8 ms^{-1}. However, in many cases katabatic wind pulses of this second group had still lower wind speeds. The synoptic conditions were on these occasions forcing south-easterly geostrophic winds over Heimefrontfjella, thus enhancing the katabatic winds. As similar conditions also characterized the calm periods between the katabatic events this seems to support the idea that it takes time to produce new cold air in a small drainage area before another katabatic event begins (Schwerdtfeger 1984). The formation of stagnant air inside SBB between the katabatic events also supports it. When the supply of cold air is larger and therefore the sloped inversion pressure gradient force supposedly is larger, the katabatic flow is triggered by a small variation of the surface pressure. This is exemplified by the close correspondence between strong winds in SBB and minima for air pressure north-west of Neumayer station.

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