Orographic clouds in north Victoria Land from AVHRR images

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Received June 1995

ABSTRACT. Orographic clouds over north Victoria Land, East Antarctica, have been observed in Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. These occasional clouds are discussed through analysis of their spectral features in AVHRR data. Temporal occurrence, spatial extension, and direction of the clouds are also discussed in relation to meteorological data for two periods characterised by katabatic winds, in December 1992 and January 1993.

Contents

Introduction

Orographic clouds are generated by lee waves (Atkinson 1981) originating when airflows move over an obstacle. These 'atmospheric waves' force air to higher levels at lower temperature. At the saturation altitude, water vapour condenses, forming supercooled water droplets that, depending on temperature, can originate ice crystals. Orographic clouds developing at low altitude, just above the obstacle, are called foehnwalls. These clouds are characterised by a relatively high temperature and do not extend over wide distances. Orographic clouds forming at high altitudes at some distance from the obstacle are called orographic cirrus. These clouds are characterised by a relatively low temperature and can extend for hundreds of kilometres downwind.

Orographic clouds have been widely observed and studied at mid-latitudes (Atkinson 1981; Scorer 1986, 1990). A recent extensive collection of Advanced Very High Resolution Radiometer (AVHRR) data over north Victoria Land, East Antarctica, carried out as part of the Italian National Antarctic Program, has enabled the observation of orographic clouds over different areas. The aim of this paper is to present observations and to discuss features of these clouds resulting from AVHRR data analysis.

Study area

North Victoria Land is characterised by the Transantarctic Mountains, which stand roughly between the coast and the inner plateau (Fig. 1). The region is dominated by strong katabatic winds, which are cold airflows draining from the plateau to sea level (Schwerdtfeger 1984; Bromwich 1989; Bromwich and others 1990, 1993), and which frequently take place during the entire year, significantly influencing the atmospheric circulation (Parish 1988).

Data and observations

The AVHRR sensor installed on NOAA's satellites provides measurements of the Earth's surface with 1.1 km resolution at nadir in five spectral bands: red (channel 1: 0.58–0.68 μm), near infrared (channel 2: 0.72–1.10 μm), middle infrared (channel 3: 3.55–3.93 μm), and thermal infrared (channel 4: 10.3–11.3 μm and channel 5: 11.5–12.5 μm). Measurement in different regions of the electromagnetic spectrum results from different radiative processes: in channels 1 and 2, it is due to solar radiance reflected by the Earth's surface; in channel 3, it is due to the sum of solar-reflected and terrestrial-emitted radiance; and in channel 4, it is only due to terrestrial-emitted radiance. The AVHRR images discussed — acquired by the HRPT (High Resolution Picture Transmission) receiving station installed at Terra Nova Bay — were collected as part of the 1992/93 scientific expedition of the Italian National Antarctic Program.

Clouds strictly related to orography, developing over north Victoria Land, were clearly noticed in NOAA-11 and NOAA-12 AVHRR imagery taken on 25–28 December 1992 and 2–7 January 1993, with Sun zenith angles between 55° and 75°. The analysis of 37 AVHRR images taken during the two periods showed that:

1. orographic clouds were more spatially extended in the first period;
2. foehnwalls regularly occurred during the December period and occasionally in January (that is, they only appeared in some images from 4–6 January); and
3. orographic cirrus frequently occurred during the January period and exceptionally on 27 December.

In situ observations reported that both the December and January periods were preceded by snowfalls (~20 cm on 23–24 December, and less than 5 cm on 30–31 December). Meteorological data from US (Keller and others 1994, 1995) and Italian (personal communication, P. Grigoni, L. De Silvestri, and A. Pellegrini, February 1996)

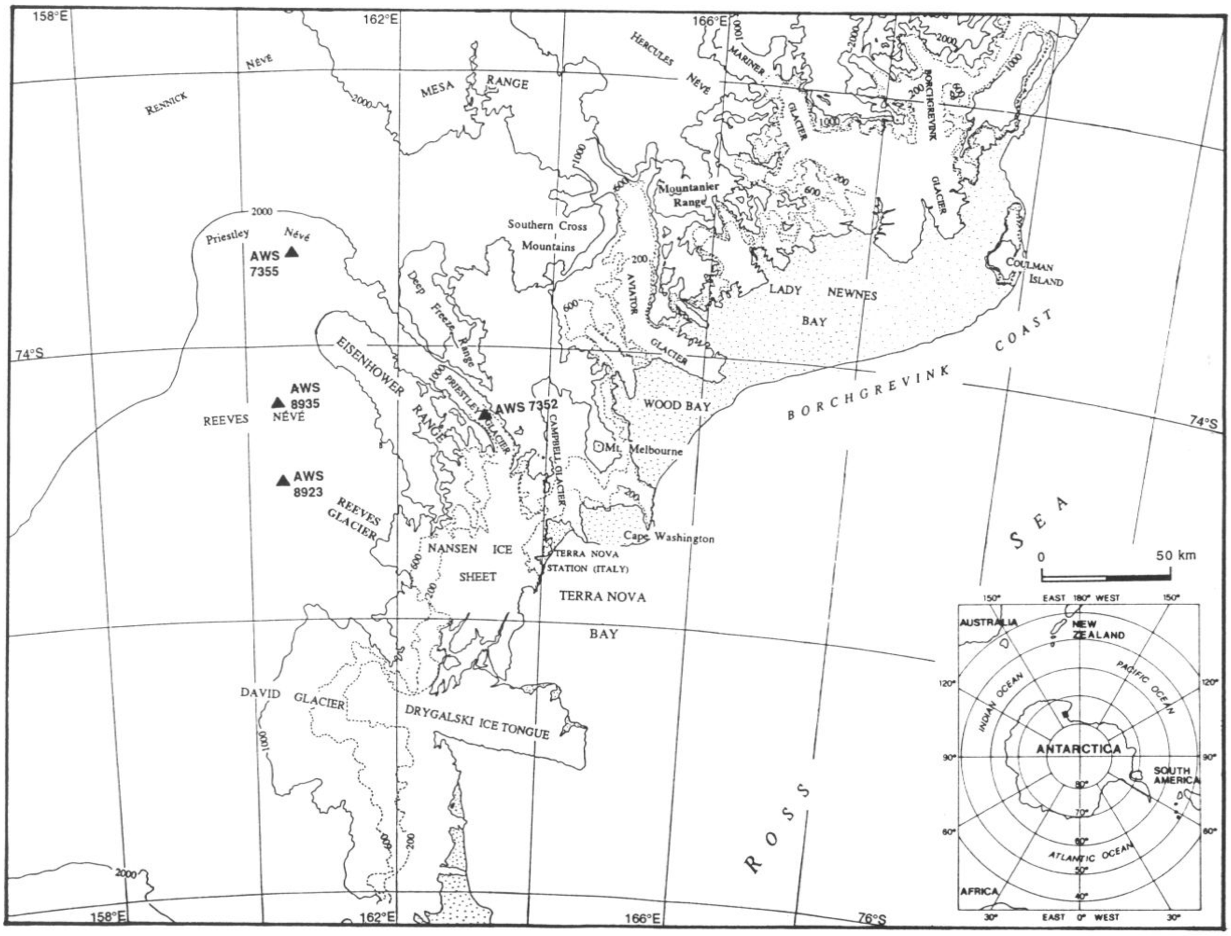

Fig. 1. Map of the geographical area covered by the study. Triangles indicate location of automatic weather stations (AWS 8923, AWS 8935, AWS 7352, and AWS 7355) providing meteorological data used in the study.

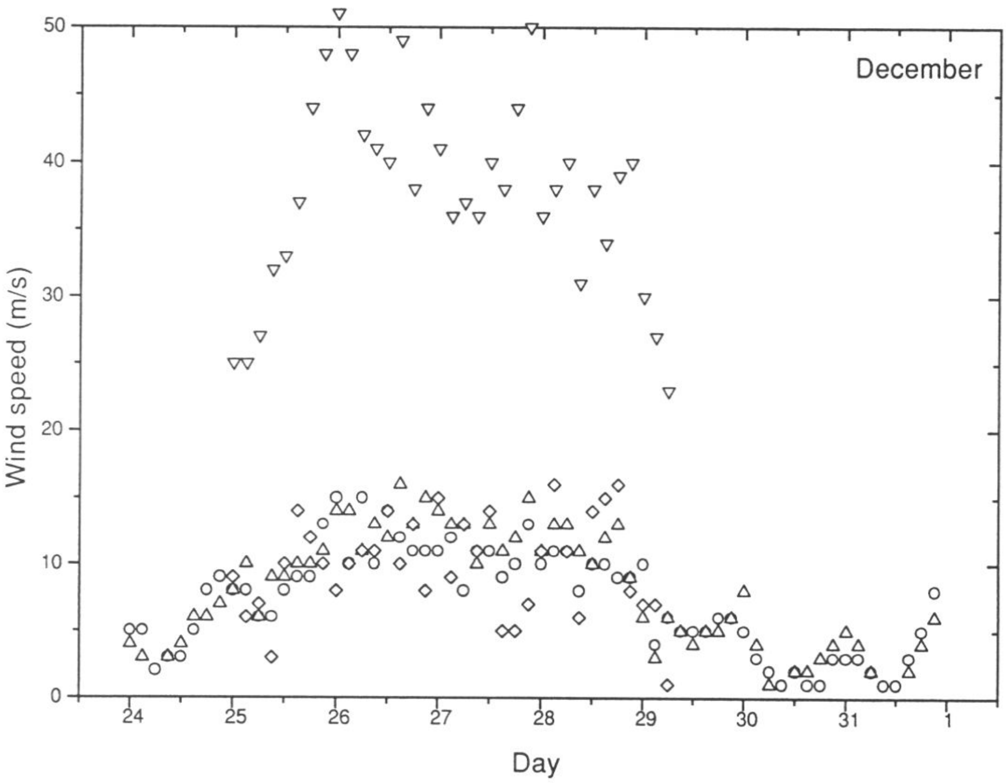

Fig. 2. Wind speed from automatic weather stations (triangles up: AWS 8923; circles: AWS 8935; triangles down: AWS 7352, diamonds: AWS 7355) during the December study period.

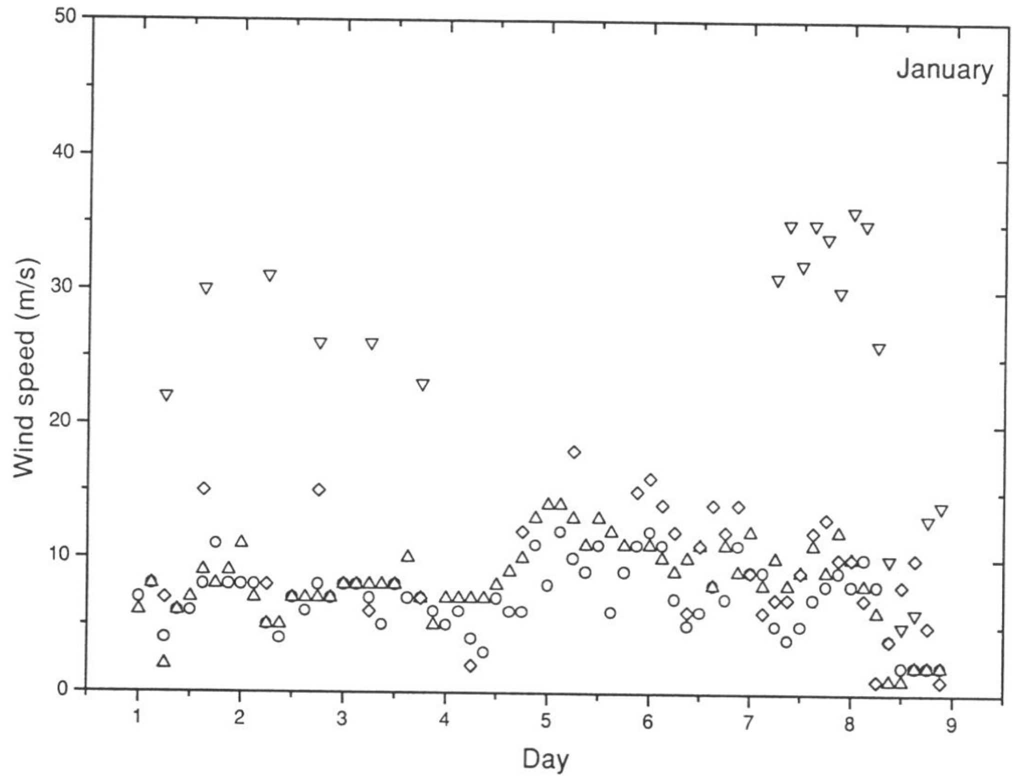

Fig. 3. Wind speed from automatic weather stations (triangles up: AWS 8923; circles: AWS 8935; triangles down: AWS 7352, diamonds: AWS 7355) during the January study period.

automatic weather stations AWS 8923 (160° 29'E, 74° 29'S, elevation 1525 m), AWS 8935 (160° 22'E, 74° 13'S, elevation 1772 m), AWS 7352 (163° 09'E, 74° 15'S, elevation 650 m), and AWS 7355 (160° 38'E, 73° 38'S, elevation 1983 m), indicate (Figs 2–5) that katabatic winds were taking place in the study area when orographic clouds were recorded (the extraordinarily strong winds at AWS 7352 were due to air accelerated by a pressure gradient oriented along the narrow valley of the Priestley Glacier). This finding suggests that katabatic winds can 'trigger' the formation of orographic clouds in wide areas of north Victoria Land.

The higher intensity of katabatic winds from the plateau during the December period, compared to the January period, appears to be related to the higher temporal occurrence and the higher spatial extension of foehnwalls

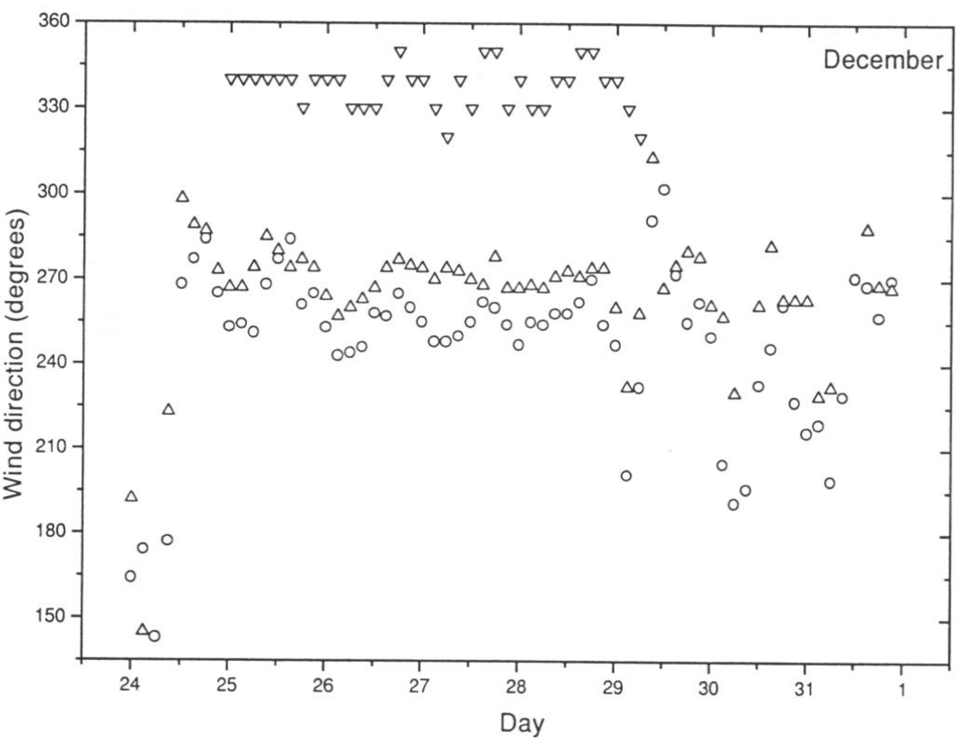

Fig. 4. Wind direction from automatic weather stations (triangles up: AWS 8923; circles: AWS 8935; triangles down: AWS 7352, diamonds: AWS 7355) during the December study period.

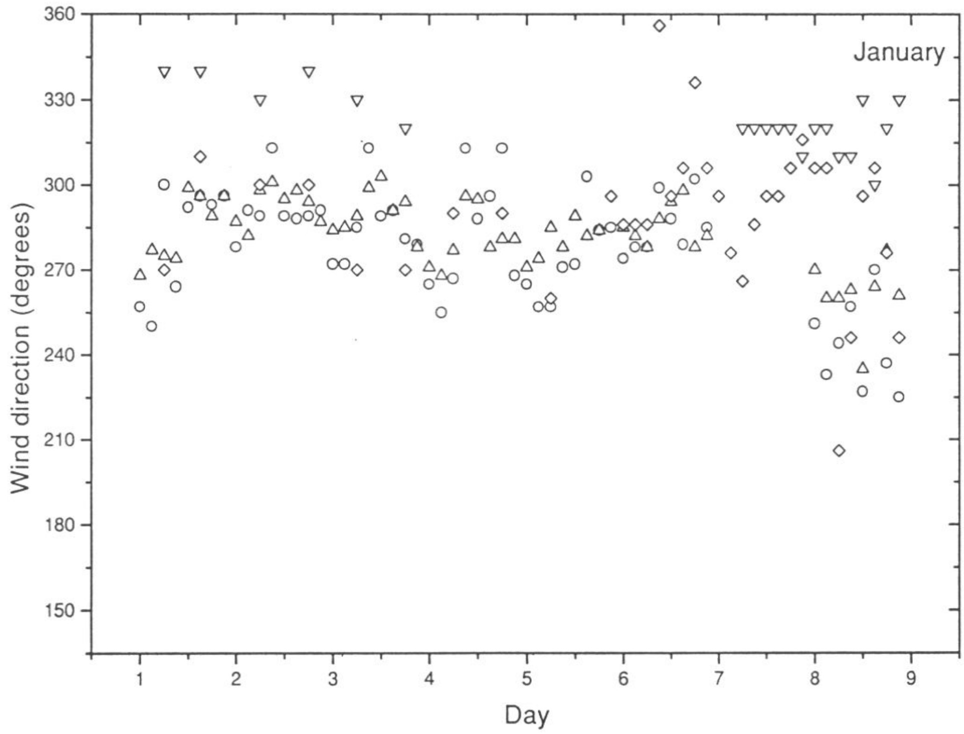

Fig. 5. Wind direction from automatic weather stations (triangles up: AWS 8923; circles: AWS 8935; triangles down: AWS 7352, diamonds: AWS 7355) during the January study period.

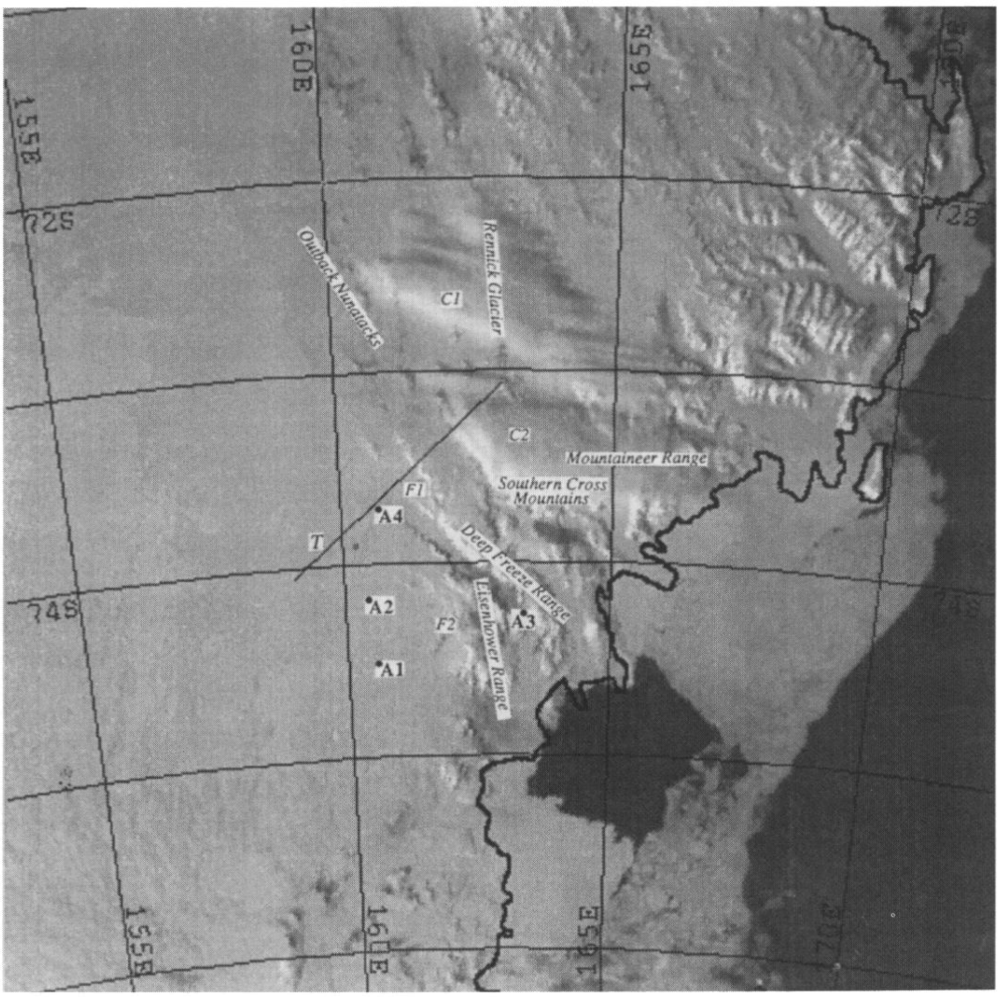

Fig. 6. AVHRR scene of Victoria Land from orbit #21941, channel 2 (27 December 1992). Increase in brightness means increase in top of the atmosphere albedo (ranging from 1 to 30%). C1 and C2 indicate orographic cirrus, while F1 and F2 indicate foehn-walls. T indicates transect outlined in Figure 9. A1, A2, A3, and A4 indicate locations of automatic weather stations AWS 8923, AWS 8935, AWS 7352, and AWS 7355, respectively.

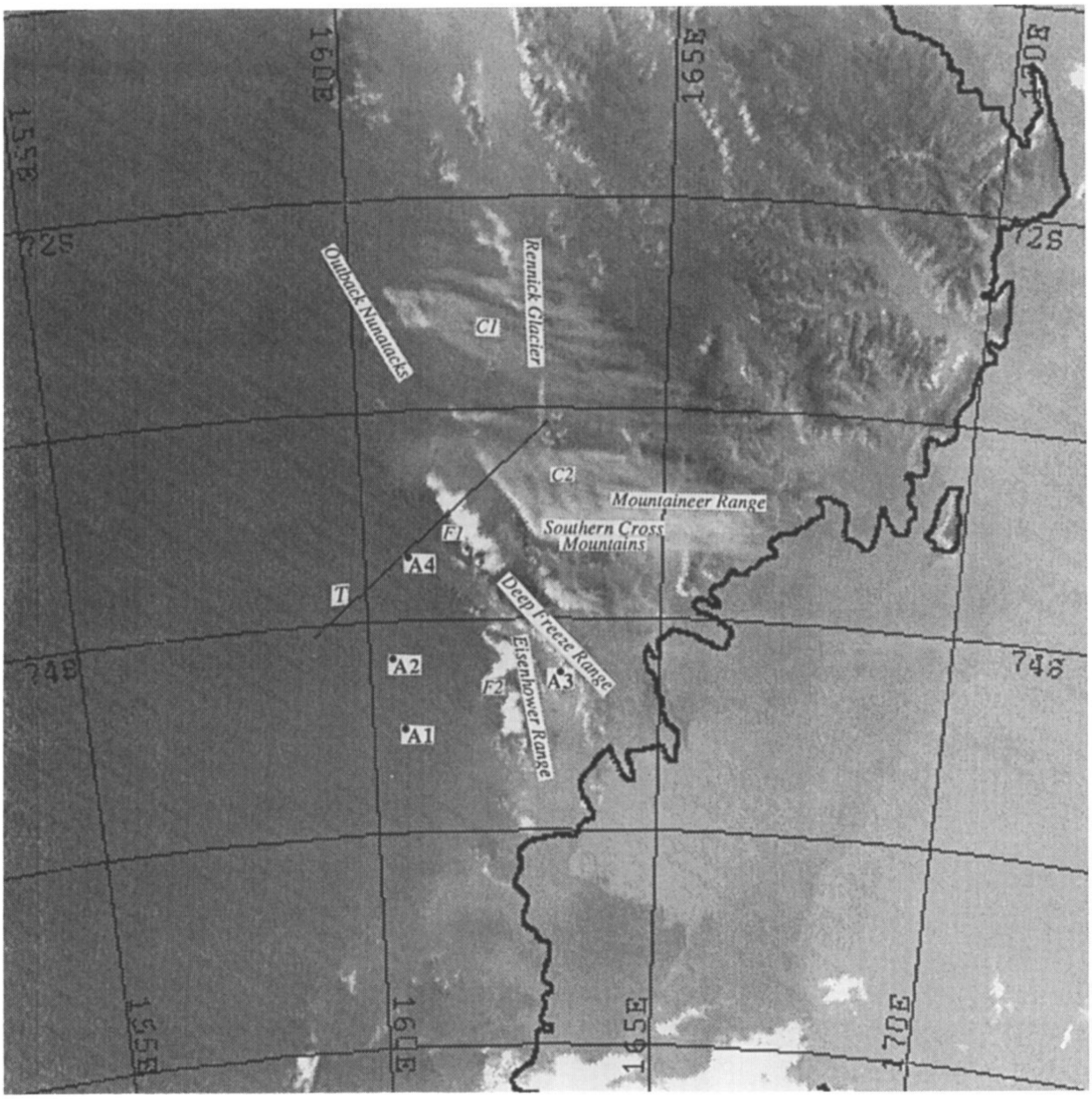

Fig. 7. AVHRR scene of Victoria Land from orbit #21941, channel 3 (27 December 1992). Increase in brightness means increase in brightness temperature (ranging from 19 to –20°C). C1 and C2 indicate orographic cirrus, while F1 and F2 indicate foehnwalls. T indicates transect outlined in Figure 9. A1, A2, A3, and A4 indicate locations of automatic weather stations AWS 8923, AWS 8935, AWS 7352, and AWS 7355, respectively.

during the first study period. The higher temporal occurrence of orographic cirrus during the January period could be explained by a higher vertical stability of the atmosphere. Unfortunately the latter statement cannot be confirmed by radiosounding data taken at Terra Nova Bay because of their unavailability on days characterised by strong winds.

Discussion on a case study

Figures 6, 7, and 8 display an AVHRR scene for 27 December 1992 of north Victoria Land in channels 2, 3, and 4, respectively. These images have been selected specifically to describe orographic clouds from AVHRR data because of the simultaneous presence of both foehnwalls and orographic cirrus. Data in channel 2 are in albedo units, while data in channels 3 and 4 are in brightness temperature units (Lauritson and Nelson 1979). Orographic cirrus develop eastward: cirrus C1 originates from the Outback Nunataks and extends over the Rennick Glacier, and cirrus C2 originates from the North Deep Freeze Range and extends over the Southern Cross Mountains and the Mountaineer Range. Foehnwalls develop over two major sites: foehnwall F1 just above the North Deep Freeze Range, and foehnwall F2 just above the Eisenhower Range. All these orographic clouds in channel 3 appear brighter than the surrounding snow/ice surfaces, even though their brightness temperature in channel 4 is lower, because of the presence of water droplets and/or very small ice crystals that have high reflectivity in the middle infrared (Arching and Childs 1985). Higher brightness of foehnwalls, compared to that of orographic cirrus,

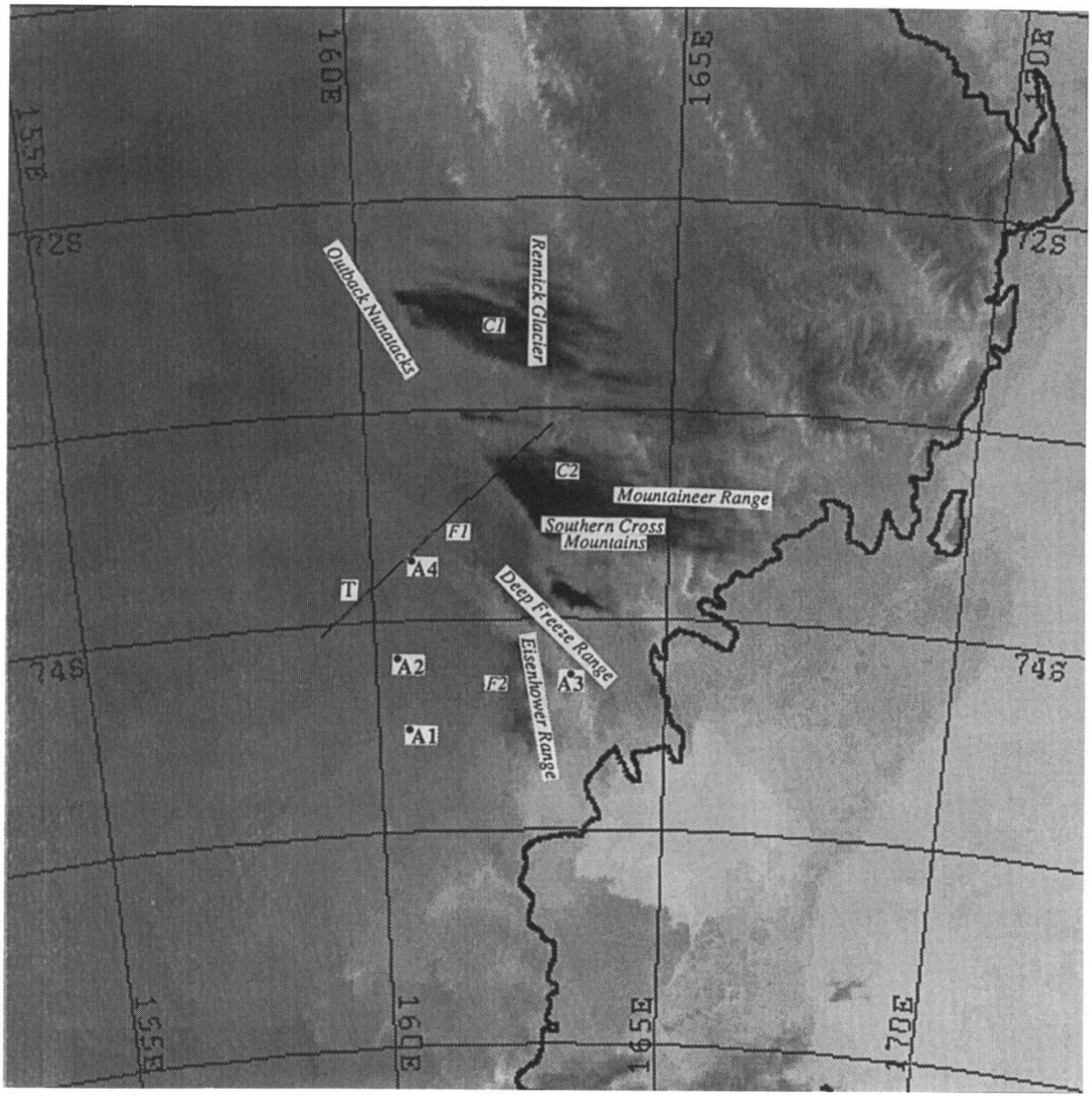

Fig. 8. AVHRR scene of Victoria Land from orbit #21941, channel 4 (27 December 1992). Increase in brightness means increase in brightness temperature (ranging from –1 to –55°C). C1 and C2 indicate orographic cirrus, while F1 and F2 indicate foehnwalls. T indicates transect outlined in Figure 9. A1, A2, A3, and A4 indicate locations of automatic weather stations AWS 8923, AWS 8935, AWS 7352, and AWS 7355, respectively.

could be due to occurrence of a relatively higher temperature preventing formation of ice crystals from supercooled water droplets (in general, ice crystals are larger than water droplets and consequently have lower reflectance) and/or a higher concentration of water droplets produced by relatively high humidity in the lowest atmospheric layer due to sublimation of snow (Schmidt 1982; Kodama and others 1985) transported by katabatic winds. A decrease in brightness with distance from the origin of orographic cirrus is caused by a reduction of ice crystals and/or water droplets due to evaporation. Foehnwalls exhibit a channel 4 brightness temperature of about –25°C, almost constant over the entire cloud surface. This brightness temperature has values close to that of the underlying snow surface, and it makes the detection of foehnwalls in channel 4 imagery difficult. Channel 4 brightness temperature of orographic cirrus ranges from –45°C, where the clouds originate, up to the brightness temperature of the underlying surface (that is, –25 to –20°C), where the clouds dissolve. Texture and shadows in channel 2 imagery clearly indicate the existence of orographic cirrus. Observation of foehnwalls in channel 2 is more difficult because of:

1. the homogeneity of the cloud and the low contrast created by the underlying snow cover; and
2. the absence of relevant shadows (due to the relatively low altitude from the underlying surface).

Figure 9 shows orography and schematic representation of clouds for the transect T in Figures 6–8. T has been chosen in the area where both foehnwalls and orographic cirrus develop. Observing the orography, it can be de-

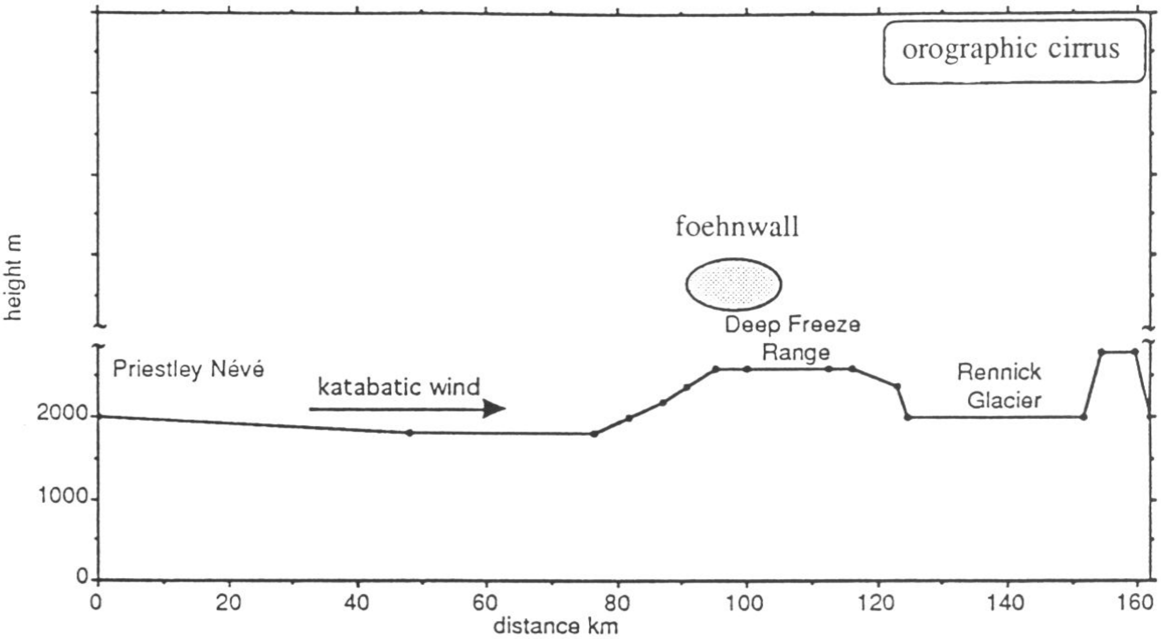

Fig. 9. Orography and schematic representation of clouds corresponding to transect T shown in Figures 6–8.

duced that the Deep Freeze Range influences airflows (that is, katabatic winds) descending from the plateau, inducing vertical oscillation of air over and after the obstacle. If the air forced over the mountains is taken to an altitude where saturation can occur, water droplets form and originate the observed foehnwalls, which extend for a few kilometres. According to the phase of lee waves forming because of the obstacle, at some height (generally a few kilometres) and distance from the ridge, at the water-saturation altitude, there could be formation of water droplets quickly freezing and forming ice particles that originate the observed orographic cirrus, extending up to 100 km.

Altitude of clouds has been estimated by assuming that their brightness temperature in channel 4 is close to their actual physical temperature (that is, assuming that cloud emissivity is close to 1). From intercomparison of channel 4 cloud-brightness temperatures with radiosounding air temperatures taken at the beginning of the first study period (Fig. 10), foehnwalls and orographic cirrus in Figures 6–8 have been roughly located at 3000–3500 m and 7000–8000 m above sea level, respectively.

The direction of the orographic cirrus in Figures 6–8 is in agreement with atmospheric circulation data (D.H. Bromwich, personal communication, February 1996) reported by meteorological charts from the European Center for Medium-Range Weather Forecasts (ECMWF). The 300-hPa chart (close to the cirrus level) at 1200 UTC (the closest to 8:20–8:25 UTC time of imagery detection) shows that local circulation was from the west, demonstrating the role of the free atmospheric circulation in generating the orographic cirrus C1 and C2 appearing in Figures 6–8.

The direction of foehnwalls is in agreement with the wind directions recorded by the closest automatic weather stations. Foehnwall F1 has a northeast direction, in agreement with the wind direction (~240°) recorded by AWS 7355 and AWS 8935 at the time of imagery detection. The eastward direction of foehnwall F2 is in agreement with the wind direction (273°) recorded by AWS 8923. The direction of foehnwalls is also in agreement with mean wind-field information derived from surface aeolian morphologies (sastrugi, snow drifts, windscoops, and drift plumes). In fact, even though aeolian morphologies on epiglacial surfaces of the Reeves Névé have shown that prevailing winds converge to the Reeves Glacier (Bromwich and others 1990) rotating from west to northwest and north-northwest, aeolian morphologies at the top of mountains (Eisenhower Range, Deep Freeze Range, Mount Melbourne, and Southern Cross Mountains) have shown that prevailing winds are from the west (Frezzotti, in press). Overall observations suggest a different wind behaviour as a function of altitude from the surface: at low altitude, winds follow orography and converge to the Nansen Ice Sheet through the Priestley and Reeves valleys, while at higher altitude, winds cross over the mountains according to a prevailing eastward direction.

Conclusion

AVHRR images of north Victoria Land taken during the 1992/93 Italian Antarctic Expedition have shown the presence of orographic clouds. Their occurrence has been related to the existence of katabatic winds and peculiar orography. Data in AVHRR channel 3, highly sensitive to water phase, have shown their capability of discriminating orographic clouds from the underlying snow and ice surfaces in imagery. Temporal occurrence, spatial extension, and direction of foehnwalls have been shown to be related to surface meteorological observations. Direction of orographic cirrus has been shown to be in agreement with the free atmospheric circulation. The temporal occurrence

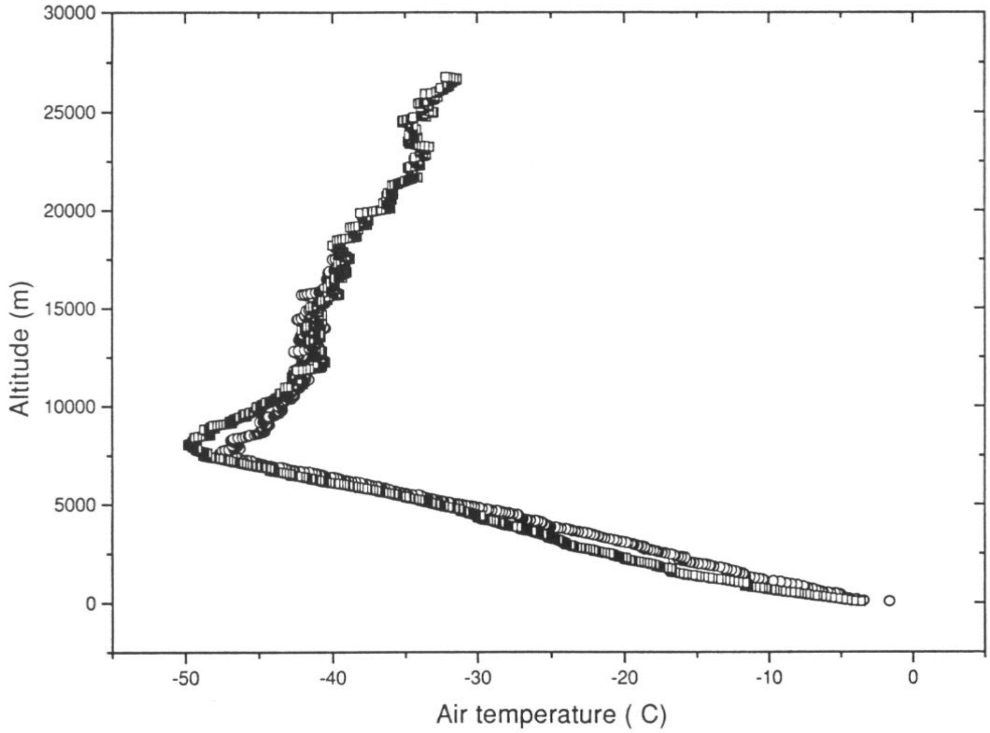

Fig. 10. Atmospheric temperature profiles from radiosoundings taken at Terra Nova Bay (triangles: 0:00 UTC on 25 December; circles: 0:00 UTC on 26 December).

of orographic cirrus has been assumed to be related to atmospheric stability. However, further investigations supported by systematic radiosoundings are required to confirm the latter assumption.

Acknowledgements

The authors are endebted to Dr David H. Bromwich for supplying the free atmospheric circulation data of 27 December 1992. The authors would also like to thank Paolo Grigioni, Lorenzo De Silvestri, and Andrea Pellegrini for providing the unpublished AWS data; and Professor Richard S. Scorer for the helpful discussions on the AVHRR pictures presented. Massimo Frezzotti has been supported by the Italian National Antarctic Program.

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