A Mesoscale Vortex over Halley Station, Antarctica

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ABSTRACT

A detailed analysis of the evolution and structure of a mesoscale vortex and associated cloud comma that developed at the eastern edge of the Weddell Sea, Antarctica, during the early part of January 1986 is presented. The system remained quasi-stationary for over three days close to the British research station Halley (75°36'S, 26°42'W) and gave severe weather with gale-force winds and prolonged snow.

The formation and development of the system were investigated using conventional surface and upper-meteorological observations taken at Halley, analyses from the U.K. Meteorological Office 15-level model, and satellite imagery and sounder data from the TIROS-N-NOAA series of polar orbiting satellites. The thermal structure of the vortex was examined using atmospheric profiles derived from radiance measurements from the TIROS Operational Vertical Sounder. Details of the wind field were examined using cloud motion vectors derived from a sequence of Advanced Very High Resolution Radiometer images.

The vortex developed inland of the Brunt Ice Shelf in a strong baroclinic zone separating warm air, which had been advected polewards down the eastern Weddell Sea, and cold air descending from the Antarctic Plateau. The system intensified when cold, continental air associated with an upper-level short-wave trough was advected into the vortex. A frontal cold band developed when slantwise ascent of warm air took place at the leading edge of the cold-air outbreak. Most of the precipitation associated with the low occurred on this cloud band.

The small sea surface-atmospheric temperature differences gave only limited heat fluxes and there was no indication of deep convection associated with the system. The vortex was driven by baroclinic forcing and had some features in common with the baroclinic type of polar lows that occur in the Northern Hemisphere.

1. Introduction

Studies of satellite imagery and conventional surface meteorological observations have revealed many mesoscale vortices over the high-latitude ocean areas of both hemispheres (Bromwich 1989; Businger and Reed 1989; Stretten and Troup 1973; Turner and Row 1989). Many of these vortices form in the weak, low-level baroclinic zones close to the edge of the sea ice and are relatively short-lived features (Scorer 1986). Some of the vortices develop, however, into major mesoscale circulations with gale-force surface winds and heavy precipitation. Such systems, when occurring poleward of the main polar front in the Northern Hemisphere, are referred to as polar lows (Rasmussen 1979, 1983, 1985) and are of considerable interest to operational meteorologists because of their severe weather and impact on polar maritime operations. Polar lows only develop in a few areas of the Northern Hemisphere where very cold arctic airstreams cross relatively warm ocean currents. Until recently, “classic” polar lows were thought to occur only in the Barents and Norwegian seas and to the south of Iceland. More recently, however, polar lows have been identified in the Gulf of Alaska (Businger 1987) where similar conditions occur.

In the Southern Hemisphere the location of the major landmasses and the prevailing ocean currents does not allow significant transport of warm water into the high-latitude areas, so that classic polar lows are not found. Nevertheless, studies of satellite imagery from the ocean areas around the Antarctic do show subsynoptic-scale vortices that exhibit some of the characteristics of polar lows. One of the earliest studies of Southern Hemispheric vortices was carried out by Stretten and Troup (1973) and, although this work was mainly concerned with midlatitude systems, the authors noted many small vortices at high latitude and stressed that “the frequency of non-frontal developments increases towards higher latitudes.” The very limited number of Southern Hemispheric upper-air stations has prohibited the detailed investigation of the structure of these systems and their comparison with mesoscale systems in the Northern Hemisphere. In the last few years, however, satellite sounding techniques using infrared...
and microwave radiometers on polar orbiting satellites have developed to the point where temperature profiles at high horizontal resolution allow the study of meso- and synoptic-scale systems in remote regions where few radiosonde ascents are available.

This paper examines one vigorous mesoscale vortex that developed close to the Antarctic coast near the British research station Halley (75°36'S, 26°42'W) during the period 2–6 January 1986. The system formed over the immediate interior of the continent and developed into a small, 300-km diameter vortex over the ice-free ocean on the eastern side of the Weddell Sea. Over the following two days the vortex grew into a major mesoscale disturbance with a diameter of approximately 600 km and gave winds of almost 40 kt at Halley Station on the Brunt Ice Shelf. Most of the precipitation associated with the system occurred on a comma-shaped band of cloud that spiraled into the center of the low. Over 24 h of snowfall occurred at Halley as the cloud band moved inland during its mature phase. During January, Halley usually experiences two or three major depressions that bring moderate snowfall and warm air from lower latitudes. These systems usually approach via the Weddell Sea and have many of the characteristics of midlatitude depressions. Vigorous, mesoscale depressions forming poleward of the main polar front, such as the system examined in this paper, are much less frequent than midlatitude lows tracking poleward; however, even amongst the polar depressions occurring around Halley over the last few years, the case examined here is exceptional because of its quasi-stationary nature over a 3-day period.

Because of the very limited amounts of synoptic data available around the Weddell Sea, extensive use has been made of satellite observations and some analyses from numerical forecast systems. Because of the different characteristics of the observations and the problems in producing numerical analyses around the Antarctic, the following section is concerned with a discussion of the resolution and reliability of the various forms of data. This is followed by a description of the broad-scale synoptic situation in which the vortex developed using the numerical and hand-drawn analyses. The detailed evolution of the system is then examined using high-resolution satellite data and isentropic analyses derived from the model fields and satellite temperature soundings.

2. Data

a. Synoptic observations

With the sparse operational observing network in the Antarctic, only a single station (Halley) was close enough to provide useful surface and upper-air observations. Halley routinely makes 3-h surface observations and daily radiosonde ascents at 1200 UTC. These data were available throughout the period of interest, except for the upper-air data on 4 and 6 January, which were lost because of technical problems. Upper-air winds are determined at Halley using the Omega very low frequency (VLF) navigation system. Problems experienced in receiving sufficiently strong VLF signals result occasionally in missing wind data at some levels of the radiosonde ascents. All the synoptic data referred to in the text are for Halley Station.

b. Satellite imagery

Data from the TIROS-N–NOAA series of polar orbiting satellites (Schwab 1978, 1982) have been used extensively in this case study. Digital, NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) imagery for the relevant period were obtained on tape from the National Environmental Satellite Data Information Service (NESSDS) of NOAA (National Oceanic and Atmospheric Administration). The global area coverage (GAC) (Kidwell 1988) imagery obtained had a nominal spatial resolution of 4 km at nadir and a thermometric resolution of about 0.1 K. These data were calibrated using the technique of Lauritson et al. (1979) and remapped onto a polar stereographic projection to facilitate comparison with other forms of data. The imagery was used primarily to determine the location of the main cloud systems and to derive cloud-top temperatures. For 5 January, when the system had reached its mature phase, the wind field around the vortex was examined using cloud-track winds derived from a sequence of AVHRR images from consecutive satellite passes. The winds were produced using the manual and automatic wind-vector generation techniques described by Turner and Warren (1989).

c. Satellite sounder data

The three-dimensional temperature structure was investigated using soundings from the TIROS Operational Vertical Sounder (TOVS) (Smith et al. 1979). The raw TOVS data were converted into temperature profiles using software based on an early version of the Local Area Sounding System (LASS), which is run operationally by the U.K. Meteorological Office (Eyre and Jerrett 1982; Turner et al. 1985). This scheme is based on the statistical inversion method of Smith and Woolf (1976), but uses synthetic regression coefficients produced for the Antarctic using several years of Halley radiosonde data. The TOVS processing package also incorporates the sequential estimation cloud-clearing scheme developed by Eyre and Watts (1987). This software allowed soundings to be produced at a horizontal resolution of approximately 80 km, which is much higher than that available with the SATEM (satellite temperature) messages distributed globally over the Global Telecommunications System by NESDIS. For this study, the raw, full resolution TOVS data for the first week of January were obtained from NESDIS on tape and processed on the British Antarctic Survey ARAMIS (Antarctic Research in Applied Meteorology, Imaging and Sounding) remote sensing system (Turner
The atmospheric profiles produced from TOVS radiances lack vertical resolution and for this reason have received only limited use in relatively data-rich areas such as the North Atlantic. In an area as remote as the Antarctic, however, where very few other observations are available, the TOVS retrievals offer the only means of obtaining high-resolution data on the thermal field. Provided that the limited vertical resolution of the data is taken into account the soundings can give valuable information for use in case studies. Because of the nature of satellite soundings the retrievals obtained are more representative of the mean temperature of atmospheric layers than particular layers. For this reason, most use has been made of the 1000–500-mb thickness fields derived from the TOVS. A further limitation is that the scheme does not produce reliable soundings over land with high elevation so the soundings used were limited to the oceans and the low coastal area. This was not a serious limitation as the main developments occurred away from the high Antarctic Plateau. Also, when there is a large surface inversion, as, for example, on 3 January, the absolute values obtained by the retrieval scheme are likely to be in error although the relative pattern will be correctly shown. Humidity profiles derived from the TOVS radiances are extremely unreliable and are not used generally in numerical forecasting systems. We have therefore not used these data in this study.

d. Model fields

Selected fields from the U.K. Meteorological Office 15-level model, operational, numerical analysis system were obtained for the southern Weddell Sea area. These were the “update” analyses produced at T + 11 h 30 min that incorporate late observations, including data from the Southern Hemisphere, which are often missing in the earlier analyses produced at T + 3 h 20 min. Fields obtained included temperature, wind velocity, and geopotential height at four tropospheric levels. It is worth noting that despite the small size of the circulation and the wide spacing of the conventional observational network in the area, the analysis did have a vortex in approximately the correct position. This is probably due to the Halley observations that were regularly incorporated into the analyses. The model fields were mainly used within an isentropic analysis to examine the large-scale flow.

e. Hand-drawn analyses

The surface pressure and 500-mb contour Southern Hemisphere hand-drawn analyses for the first week of January were obtained from the Central Forecasting Office at Bracknell. These were produced by analysts who made use of the 15-level model fields, satellite imagery, and all other available data. The resulting analyses are therefore felt to be as good an estimate as possible of the synoptic-scale conditions in a very data-sparse area. The 500-mb charts have been modified in light of the TOVS 500–1000-mb thickness retrievals.

f. Water vapor imagery

As the TOVS humidity retrievals are of very poor quality, they were not used directly. Instead, the 6.7-μm water vapor channel data of the High-Resolution Infrared Radiation Sounder (HIRS) were used as low-resolution imagery (Turner and Ellrott 1992). These data have the same characteristics as Meteosat and GOES (Geostationary Operational Environmental Satellite) water vapor imagery, but have a horizontal resolution of approximately 40 km and a swath width of 2200 km. The 6.7-μm channel weighting function peaks at a height that is dependent on the amount of water vapor in the atmospheric column. If less water vapor is present, the TOVS channel will receive radiation from the warm, lower layers of the atmosphere giving high brightness temperatures. Correspondingly, when the mid- to upper troposphere is moist, radiation will be received from higher levels, with the brightness temperatures being colder. Under typical Antarctic summer conditions the peak in the weighting function varies between 300 mb for 90% humidity and 600 mb for 20% humidity. The water vapor images presented in this paper are shown in the conventional sense with the darker (lighter) areas representing dryer (moister) conditions in the mid- to upper troposphere.

Further analysis of the images

This study is extensively based on temperature profiles from satellite sounding instruments. These data have been shown to have a number of problems, including poor vertical resolution, difficulties in cloud areas because of the contaminating effects of the semi-transparent clouds, major problems over high ground and ice surfaces, and biases at the edges of the swath. To check that the TOVS retrievals produced in the region of the eastern Weddell Sea are realistic, a comparison was carried out of the profiles near to Halley, Neumayer, and SANAE (South African National Antarctic Expedition) stations with the radiosonde ascents made as part of the routine meteorological programs. Figure 1 shows the rms and mean differences between the radiosonde profiles and the nearest TOVS retrievals using a collocation criteria of 100 km and 6 h, using all collocations during 1, 2, 3, and 5 January 1986. This shows an rms error of around 2°C throughout the troposphere and lower stratosphere. The mean difference is positive and around 1°C over the whole troposphere but becomes negative in the stratosphere. These figures suggest that there are no major errors in the satellite soundings providing that they can be presented in a detailed picture of the thermal structure where no in situ upper-air data are available. A more detailed analysis of the performance of statistical and physical TOVS retrieval schemes in the Antarctic coastal region is given in Lachlan-Cope (1992).
Fig. 1. Root-mean-square and mean error of TOVS retrievals compared to Halley, SANA, and Georg von Neumayer radiosonde ascents for the period 2–6 January 1986.

3. Synoptic overview

The vortex developed during the first week of January 1986 in the eastern part of the Weddell Sea (see Fig. 2 for the locations of the various places referred to in the text).

The sequence of 1200 UTC surface pressure and 500-mb contour charts for the period 1–6 January 1986, as drawn by the Central Forecasting Office of the U.K. Meteorological Office, is shown in Figs. 3a and 3b, respectively. Only minor modifications have been made to the charts drawn by the analysts at Bracknell although every effort was made to ensure consistency with the 1000–500-mb TOVS thickness retrievals.

Throughout the first six days of January, a large area of high pressure remained quasi-stationary over the Antarctic Plateau and dominated the interior of the continent on both the surface and 500-mb charts. On 1 January, three low pressure systems were located in the Antarctic Peninsula–Weddell Sea region.

(i) Low M—a mobile surface low pressure system was centered over the tip of the Antarctic Peninsula with an occluded front extending toward the northeast.

(ii) Low S—a deep, barotropic low pressure system was quasi-stationary north of SANA Research Station (70°S, 2°W) at latitude 62°S, some 1100 km northwest of Halley.

(iii) Low B—a surface and 500-mb low in the Bellingshausen Sea.

During 1 January a strong, zonal easterly flow existed over the latitude band 65°–70°S, between the Antarctic high and the low pressure belt at lower latitudes.

Fig. 2. Map of the Weddell Sea area, Antarctica.
Over the following six days, low S was a major, quasi-stationary feature in the region with a large 500-mb vortex and associated fronts lying parallel to the coast. On 2 January, low B filled and a large depression (low P) was over the eastern Bellingshausen Sea and gave limited warm advection over the Antarctic Peninsula. Ridging ahead of the depression dominated the Weddell Sea with a 500-mb high aloft. To the east of Halley, over Coats Land, a surface trough was propagating westwards.

By 3 January surface low P had become slow moving and was blocked by the anticyclone over the central Weddell Sea. The northerly flow over the western Weddell Sea had increased in the strong pressure gradient between the anticyclone and low P. At the 500 mb level the high over the Weddell Sea had intensified and an upper northerly flow was established over the peninsula ahead of a low over the Bellingshausen Sea. Over Halley, the surface analysis showed the low-level trough to have developed a separate center (low H) with a central pressure of less than 980 mb. This was evidently a fairly shallow feature, as the 500-mb contour chart indicated that the region was in an area of slack gradient between the ridge over the Weddell Sea and a trough approaching from the east. The deep center that appears on 3 January in the 500-mb contour chart, associated with the trough approaching Halley from the east, appears in the analysis on this day for the first time as it reaches the region for which TOVS retrievals are available.

The Weddell Sea anticyclone had weakened a little by 4 January but was still significant at both the surface and 500 mb. Low P remained quasi-stationary with a trough of low pressure extending southwards over the Bellingshausen Sea. The pool of warm maritime air over the southern Weddell Sea continued to move to the west. By this stage, low H had drifted a little way from the coast of Coats Land and a strong northeasterly flow was established between this low and the anticyclone over the plateau. A weak 500-mb trough associated with low S had its axis running parallel to the coast at Halley and the surface low was located under the leading edge of the trough.

During 5 January low P began to move east as the anticyclone over the Weddell Sea receded toward the northeast. Low H remained almost unchanged off Coats Land with little change in central pressure.

By 6 January the Weddell Sea had become dominated by a trough of low pressure extending from lower latitudes and had begun to absorb low H. At 500 mb an elongated low lay east–west along the southern Weddell Sea.

4. Conditions prior to cyclogenesis

The AVHRR visible and infrared images for 1541 UTC 2 January 1986 are shown in Figs. 4a and 4b (along with imagery for the remainder of the first week of January which is discussed in later sections). The visible image shows that Halley, Coats Land, and the sea area parallel to the coast were largely free of cloud and sea ice. This is consistent with the offshore winds that were reported for most of the period at Halley (Fig. 5). The only sea ice apparent is at the eastern end of the Ronne Ice Shelf. The northern and western parts of the Weddell Sea were covered with open pack ice, overlaid with fairly thin cloud. The thermal infrared channels of the AVHRR indicated that the sea surface temperatures close to Halley were in the range of 0°–2°C.

The Halley 3-h surface observations for the early part of January are plotted in Fig. 5. Between 0000 UTC 1 January and 1200 UTC 2 January the surface wind was predominantly easterly with speeds less than 10 kt. On two occasions, however, beginning at 1200 UTC 1 January and 0600 UTC 2 January the surface wind veered markedly toward the south for some time. Both of these events can be correlated with the passage of minor troughs around the low S that are indicated in the surface observations. These are also apparent in the model surface pressure analyses, but the surface pressure observations only show very minor perturbations at these times.

The sequence of radiosonde ascents made during this period is shown in Fig. 6. The ascents for the whole period of interest showed neutral or stable air over the base; however, on 1 and 2 January there was warming throughout the troposphere as air was advected toward Halley down the eastern Weddell Sea. This was accompanied by a rise in the height of the tropopause and general desiccation throughout the middle to lower layers. The upper-level winds on 1 January show easterly flow in the zonal conditions. By 2 January the upper high was dominating the Weddell Sea and the flow was a very light southwesterly near the surface. At higher levels the wind was easterly in the continued zonal flow.

The details of the thermal field over the eastern Weddell Sea were studied using the TOVS 1000–500 mb thicknesses for the first six days of January. These are shown in Figs. 7a–f. On 1 January a very slack thermal gradient existed across the Weddell Sea with a warm pool with thickness values greater than 528 dam between Halley and the east end of the edge of the Ronne Ice Shelf. On the 1640 UTC 2 January satellite pass the swath of data only extended over Coats Land and the eastern side of the Weddell Sea, although this does show considerable warming of the lower troposphere since the previous day. Thickness values of greater than 536 dam were found in the center of the warm pool, but with warming also of the southern Weddell Sea. This is attributed to advection of warm air westwards across the southern Weddell Sea coupled with anticyclonic subsidence around the ridge.

The HIRS water vapor imagery for 2 January is shown in Fig. 8a. On this day we know from the AVHRR imagery that the area around and inland of
Halley was essentially cloud-free. The water vapor imagery is therefore providing information on the tropospheric water vapor content. This shows very dry conditions over the coastal region with higher humidities across the southern Weddell Sea. Over the high plateau, however, the elevation of the terrain is at the level of the weighting function of the HIRS 6.7-μm channel and the radiances contain a significant con-
tribution from the surface and essentially provide an elevation map. The very sharp gradient at the coast shows the boundary between the very dry continental air and the more moist air over the ice-free water.

5. Cyclogenesis and development of the vortex

The vortex was first apparent on the satellite imagery for 1710 UTC 3 January; however, the meteorological
Fig. 4. Visible and infrared images from NOAA-9 afternoon overpass for 2-5 January 1986.
observations suggest that the system developed much earlier in the day. During 1 and 2 January the synoptic charts (Fig. 3) showed a trough of low pressure located inland of the research station. Figure 5 indicates that as the trough moved westwards towards Halley the surface pressure at the base fell slowly from 1200 UTC 1 January, but dropped more rapidly from 1200 UTC 2 January. Between 1800 UTC 2 January and 0600 UTC 3 January the Halley surface winds were westerly, although still light, suggesting that a low pressure center had formed just inland of the base. The cloud increased rapidly from 0 to 8 oktas of stratus between 0300 and 0600 UTC on 3 January. The surface observations suggest that the vortex crossed the base between 0600 and 0900 UTC 3 January when the wind backed from 270° to 70° and fog developed as moist air from over the ocean was advected across the cold ice. This was the time of the most rapid drop in surface pressure with falls of 13 mb occurring in the 24 h preceding 1200 UTC 3 January.
Fig. 7. 1000-500-mb thickness from TOVS retrievals from NOAA-9 afternoon overpass for 1-6 January 1986.

By 1710 UTC 3 January the vortex was located over the ice-free ocean near Halley. The AVHRR visible (0.6 μm) and infrared (11 μm) imagery for this time (Figs. 4c and 4d) shows two main cloud features:

(i) A near-circular mass of cloud with a diameter of approximately 300 km centered just offshore slightly north of the Brunt Ice Shelf. This was associated with the center of the developing vortex. Both the visible
and infrared images show that the vortex had a small, 50-km diameter, cloud-free area in its center with a hook of cloud extending outward toward the west. The infrared data give the vortex a cloud-top temperature of −9°C.

(ii) An area of higher cloud (on Fig. 4d) running in a northwest–southeast direction about 200 km to the east of the low-level vortex. This cloud is fairly thin as the coastline is clearly apparent through the cloud on the visible image. The cloud-top temperatures are around −37°C.

The 1000–500-mb thickness field at this time, derived from the TOVS data (Fig. 7c), indicates that the center of the warm pool apparent on 2 January had moved westwards to over the central Ronne Ice Shelf. This was accompanied by a marked cooling over Dronning Maud Land, which resulted in an intensification of the thermal gradient over Halley. This was orientated east–west at 20°W and was very strong from the coastal area to about 80°S. The synoptic charts suggest that the cold air was associated with the westward-moving upper-level trough south of low S.

The Halley radiosonde ascent for 1200 UTC 3 January (Fig. 6) shows that the base was on the boundary of continental and more maritime air masses and indicates:

(i) That the 1200 UTC surface temperature was the same as on 2 January.

(ii) A mixed layer from the surface to 930 mb arising from the intrusion of a tongue of cold air in the low-level south-easterly flow undercutting the upper-warm air. This is believed to be at the leading edge of the cold-air outbreak associated with the westward-moving upper-level trough.

(iii) Significant warming over the 600–800-mb layer since the previous day. This is attributed to the continued advection of warm air westwards across the southern Weddell Sea. The cold air in the surface layers with the maritime air above established a weak inversion between 950 and 800 mb. From 800 to 450 mb the environmental lapse rate was stable. The wet bulb potential temperatures \( \theta_w \) computed from this ascent show two distinct air masses: lower cold air with \( \theta_w \) of around 273 K and upper warm air with values about 280 or 281 K higher.

The infrared imagery for 1710 UTC 3 January gave cloud-top temperatures of −9°C, which the 1200 UTC radiosonde ascent would suggest should be assigned to a pressure level of about 670 mb. This would not, however, be realistic since the air is so dry at these levels. Instead it is proposed that the cloud is at a lower level and associated with the mixed layer near the surface. If this was the case it would imply continued westward propagation of the low-level cold air further deepening the mixed layer up to a level of about 850 mb. Evidence for this is provided by the Halley cloud height observations which indicated that the cloud height rose throughout 3 January. The satellite imagery and meteorological observations indicate that the low-level cold-air outbreak had some of the characteristics of a classical cold front at this time, including a drop in surface temperature and a narrow associated cloud band followed by a rapid clearance. Evidence for frontogenesis is provided by the water vapor imagery for 1700 UTC 3 January (Fig. 8b) which shows a remarkable change from the previous day. A considerable amount of cloud is apparent over SANAE and to the northeast of the vortex which appears as lighter areas on the imagery. The most striking feature, however, is a dark, comma-shaped band indicating dry air over and to the southwest of the vortex center visible in Fig. 8b and in Fig. 8c, where it is marked D. This is behind the developing front and suggests dry conditions around the 600-mb level where the peak of the water vapor channel weighting function is located. To investigate this area of descent in more detail an isentropic analysis was carried out using the wind field from the 1200 UTC 3 January U.K. Meteorological Office 15-level model analysis and thermal data from the TOVS profiles for 1700 UTC on that day. Figure 9 shows the isentropic analysis for the 283-K constant potential temperature surface around the developing low. The winds on this surface show descent inland from Halley and to the east of the dry comma, with ascent in the warm air over the Weddell Sea, ahead of the developing front. This analysis suggests that the comma in the water vapor imagery is showing an area of dry, midtropospheric air associated with the area of descent behind the cold front.

Between 1700 and 2400 UTC 3 January the low moved slightly farther out into the Weddell Sea, giving a rise in surface pressure of 6 mb at Halley; however, as the pressure inland rose during this period the gradient over the base increased giving a rise in surface wind speed to 35 kt. The infrared imagery at 2300 UTC 3 January (Fig. 10) shows the center of the vortex was still close to Halley with higher cloud extending in an arc to the northeast. Over the southern Weddell Sea there was extensive low cloud or fog. Although the cloud at the center of the vortex was largely unchanged, the cloud comma associated with the cold front had thickened and extended to higher levels as the cold air continued to undercut the warm air over the Weddell Sea and the mixed layer near the surface deepened. The AVHRR 11-μm brightness temperatures for this time show that the cloud to the rear of the front had significantly colder cloud-top temperatures than at the leading edge, suggesting slantwise ascent up the frontal surface. Convective clouds behind the front can be seen along the coast to the south of Halley indicated instability within the cold air mass.

During 4 January the vortex continued to grow due to baroclinic forcing in the region of ascent ahead of the upper-level short-wave trough. The diameter increased to 400 km as the low and high cloud elements developed and merged. The 1700 UTC 4 January im-
agery in Figs. 4e and 4f shows that much of the cloud associated with the vortex was still very thin with the thickest cloud on the frontal band (marked F). The head of the cloud comma (marked H) was still located just offshore from Halley, with the tail extending westward from the Brunt Ice Shelf, then curving southwards to the edge of the Ronne Ice Shelf. The observations from the base showed that there were 8 oktas of low cloud between 0000 and 1500 UTC but that this cleared later in the day to reveal midlevel altocumulus as the system continued to move away from the coast. The cloud associated with the cold front (marked F) was organized in two distinct bands and separated by a narrow cloud-free strip. The infrared imagery indicates that the more southerly band was at a slightly higher level and also shows a number of deep convective cells in the cold air mass. The location of some of the convective elements behind the front suggests that they
may have formed in response to enhanced lifting as the air passed over isolated regions of high ground in the coastal region around Halley.

The broad-scale thermal field, as determined from the TOVS data (Fig. 7d), had slightly weaker lower-tropospheric temperature gradients than the previous day. The change in thermal structure was due to the warm pool declining slightly and moving north over the Weddell Sea.

A cross section of potential temperature through the cold frontal surface, produced from the TOVS temperature profiles, is shown in Fig. 11. The locations of the frontal cloud bands, the upper-level dry slot, and the frontal surface are also indicated. To the west of Halley, below 600 mb, the isentropes are almost horizontal with only a very slight slope toward the front. East of the base there is a marked upward slope at all levels from the surface to above 300 mb. The cross section also shows that the low-level cloud bands were located ahead of the main lower-tropospheric thermal gradient and the surface cold front. Because of the nature of TOVS profiles, the thermal gradients are much
smoother than those found on cross sections constructed from radiosonde data.

6. The vortex: Mature phase

By 1650 UTC 5 January the vortex was at its most developed, with a large comma of cloud extending parallel to the coast and curving to the north, then west. The highest cloud was on the eastern side of the cloud band with progressively lower cloud to the west. The imagery shows a cloud-free slot located to the west of the high cloud and spiraling into the center of the vortex. This exactly corresponded with the area of low-tropospheric humidity in the water vapor imagery for this time (Fig. 8d). The tail of the comma was made up of uniform low cloud that merged into extensive cloud located over the southern Weddell Sea. The 1200 UTC Halley radiosonde data allowed the high and low cloud to be assigned to levels of around 450 and 700 mb, respectively.

The TOVS data for 1700 UTC 5 January (Fig. 7) show a further weakening of the thermal gradient over the low due to the cold pool over the plateau declining and the warm air over the Weddell Sea moving farther north. The strongest gradient is now over the southern Weddell Sea and aligned with the tail of the cloud band, which still indicates the position of the leading edge of the cold air. The thickness chart also shows that the relatively warm air had penetrated to the northern side of the vortex by this time.

The Halley upper-air ascent at 1200 UTC 5 January (Fig. 6) has stable and cold air throughout the whole troposphere with very moist air up to 510 mb and a capping, drier layer above. This transition corresponds with the top of the cloud associated with the vortex.

AVHRR imagery from three consecutive passes on 5 January were used to produce cloud-motion vectors in the region of the vortex. The wind vectors for the 800–500-mb layer are shown in Fig. 12 on top of the infrared imagery for 1700 UTC. The winds indicate two main flow regimes in the area of the front on the western side of the vortex. Immediately behind the cold front the flow is south to southeasterly and fairly light at around 10 kt. In the warm air there is extensive low cloud moving eastwards in the ascending flow up the frontal surface. These winds are somewhat stronger, but still everywhere less than 20 kt. A movie loop created from the imagery also showed that the cloud band was rotating around the vortex center, bringing thicker cloud over the base in the latter part of the day. Observations from Halley reported this to be altostratus turning into stratus fractus. The surface reports also indicated that there was no precipitation until 1500 UTC 5 January when the thicker cloud brought slight continuous snow.

During the next two days the band of cloud remained slow moving along the coast and gave continuous slight or moderate snow at Halley. The imagery (not shown) and TOVS thicknesses (Fig. 7) for 1700 UTC 6 January show a more disorganized cloud structure than on the previous day and cold, continental air pushing farther over the sea and curving around the western side of the low. Over the two days, the pressure at the base rose slowly and there was a gradual drop in surface wind speed.

7. Conceptual models

Conceptual models have been developed describing the air motion associated with the vortex at 0000 UTC 4 January and 1700 UTC 5 January. These were created using potential temperatures from the TOVS and wind data from the numerical analyses (both days) and the tracking of clouds (on 5 January). It would have been preferable to use wet-bulb potential temperature, but no reliable, quantitative information on the moisture field was available. As the TOVS data gave only a smoothed representation of the thermal field it was not possible to compute accurate vertical velocities and only general indications of ascent and descent have been presented.

Figure 13 shows the main flows as broad arrows along with schematics of the cloud, the dry band as seen on the water vapor imagery, and the location of the surface front. Two main regions of flow are apparent: first, easterly descending air in the immediate coastal region inland of Halley (descent over a considerable depth of the troposphere is implied by the dry slot in the water vapor imagery); and second, an area of low-level, slantwise ascent along the developing cloud on the cold front (this flow transported moisture from the ice-free ocean into the system).
The corresponding model for 1700 UTC 5 January is depicted in Fig. 14. By this time, the surface cold front and midlevel dry slot area over the Weddell Sea with a broad area of descending air poleward of these features. The descent takes place within about the lowest 400 mb of the troposphere. The cloud track winds for this time show a broad area of ascent spiraling into the center of the vortex from the central Weddell Sea. This flow is up to a height of approximately 500 mb as can be determined from the AVHRR cloud-top temperatures and the depth of the moist layer indicated by the Halley radiosonde ascent.

8. Comparison with Northern Hemispheric polar lows

The vortex examined in this paper had many of the characteristics of a Northern Hemispheric polar low, although the particular conditions of the Antarctic coastal region meant that different forcing mechanisms dominated. In the Northern Hemisphere, polar lows often form over ocean areas where there are large differences between the sea surface temperature and the surface air temperature. In areas such as the Barents and Norwegian seas differences of up to 30°C occur,
9. Discussion and conclusions

Satellite studies and analyses of conventional meteorological data have shown that many small vortices form over the ice-free eastern Weddell Sea area (Heinneman 1990; Turner and Row 1989) and several can usually be observed each week during the summer. This area may be prone to cyclogenesis because of increased thermal forcing over the ocean and from lee effects of the Antarctic Plateau in the predominantly

giving rise to significant deep convection and polar lows with extensive cumulonimbus cloud (Rasmussen 1985). Other systems occurring closer to the polar front resemble shallow baroclinic waves and various hybrid types of polar low are also found. Many of these systems require significant surface fluxes and the polar lows often fill after making landfall. In the area of the eastern Weddell Sea, during the summer months, the ice-free ocean usually has a sea surface temperature of 1° or 2°C and the surface air temperature is rarely below about −10°C. Climatologically, the heat and moisture fluxes in this area are therefore limited and the fetch of the air over the water is also restricted before the sea ice over the central Weddell Sea is encountered. Convection therefore plays a much smaller role in the development of Antarctic coastal vortices than in the formation of Northern Hemispheric polar lows. The strong baroclinic zones found around the coast of the Antarctic and at the boundary of the continental and maritime air masses mean that baroclinic forcing plays an important role around much of the Antarctic, as indicated by the number of mesoscale vortices identified in climatological studies (Carleton and Carpenter 1990).

Of the various polar lows documented in the literature, the system described by Harrold and Browning (1969) is most similar to the vortex described in this paper. Their polar low developed on a shallow baroclinic zone near Greenland and then moved rapidly south over the United Kingdom giving gale-force winds and heavy snow. The precipitation was organized on

Fig. 11. Cross section through the low at 0000 UTC 4 January 1986.

Fig. 12. Cloud-track winds for 1700 UTC 5 January 1986. North is upward and the image is part of the same image shown in Figs. 4g,h.
easterly flow. Recent modeling studies (Munzenberg, personal communication) have confirmed the role of topography and the generation of mesoscale cyclones through vortex stretching as air descends from the high interior of the Antarctic. Further studies and intensive data-gathering campaigns are required to confirm these conclusions, however. The majority of the vortices do not develop a significant circulation and usually dissipate within 24 h. In the case examined here, the presence of a strong low-level thermal gradient and the baroclinic forcing ahead of the upper-level short-wave trough provided favorable conditions in which the low could grow. Observations from Halley suggest that such a major mesoscale vortex occurs only every few years.

The analysis of this system has been restricted by the lack of in situ observations in the Antarctic coastal region. Although the TOVS data provided vital information on the broad-scale thermal field, they could not resolve the fine, mesoscale detail, especially in the area of the front. It is hoped that future campaigns based at Halley will provide frequent radiosonde ascents so that the structure of Antarctic vortices and fronts can be examined in more detail. One of the most useful of the satellite products was the 6.7-μm water vapor imagery that resolved the area of descent behind the developing cold front; it is felt to be a very valuable tool for synoptic and mesoscale studies in the Antarctic coastal region. The growth rate and horizontal scale of the system has been well reproduced by a simple numerical model and indicates that the system is mainly baroclinic in nature.

Recent research on Northern Hemispheric polar

![Fig. 13. Conceptual model of the low for 0000 UTC 4 January 1986.](image1)

![Fig. 14. Conceptual model of the low for 1700 UTC 5 January 1986.](image2)

lows and other high-latitude vortices has shown that there is a spectrum of vortices from those that are primarily baroclinic in origin to systems where deep cumulonimbus convection plays a major role in the development. In the Southern Hemisphere, the forcing due to surface fluxes is much lower than in the north, and baroclinic processes dominate. The type of mesoscale vortex examined in this paper, although similar to the baroclinic type of polar low, can be considered an additional class of polar vortex.

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**REFERENCES**


