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A Case study of a snowstorm at the Great Wall Station, Antarctica

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Abstract A case of a snowstorm at the Great Wall Station was studied using data of NCEP (National Centers for Environmental Prediction) analysis, in situ observations and surface weather charts. The storm occurred on August 29th, 2006, and brought high winds and poor horizontal visibility to the region. It was found that the storm occurred under the synoptic situation of a high in the south and a low in the north. A low-level easterly jet from the Antarctic continent significantly decreased the air temperature and humidity. Warm air advection at high level brought sufficient vapor from lower latitudes for the snowstorm to develop. The dynamic factors relating to strong snowfall and even the development of a snowstorm were deep cyclonic vorticity at middle and low levels, the configuration of divergence at high level and convergence at low level, and strong vertical uplift. There was an inversion layer in the low-level atmosphere during the later phase of the storm. This vertical structure of cold air at low levels and warm air at high levels may have been important to the longevity of the snowstorm.

Key words Snowstorm, Blowing Snow, Cyclone, Antarctic, Great Wall Station.

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1 Introduction

A snowstorm, also known as a blizzard, is defined as heavy snow blown by strong winds, with the horizontal visibility being less than 1000 meters and the vertical height ranging from a few meters to several hundred meters[1]. It is difficult to distinguish whether snow is falling from the sky or is being blown from the ground surface[2]. Snowstorms are one of most severe weather phenomena occurring in the Antarctica and are capable of damaging buildings, hampering sea and air traffic and even causing casualties, and thus, they pose a great threat to people wintering over in the Antarctica.

The Great Wall Station (GWS) is located on King George Island, north of the

Antarctic Peninsula, which is downstream of the generation center of South Pacific cyclones. On average, a cyclone passes over the GWS once approximately every 3 days[3]. Because of transiting circumpolar cyclones, there are dominant easterly winds (accounting for nearly 50% of all winds) and abundant snowfall[4-6]. The special climate leads to the frequent blowing of snow and snowstorms in this area. Huang studied snowstorms at the GWS in 1995, and found that most had easterly winds; however, the vertical and horizontal structures were not analyzed owing to limited available data[7].

There was a typical easterly snowstorm at the GWS on August 29, 2006 (all times that follow are local times). Among all blowing snow events (50 d) and snowstorms (6 d) at the GWS in 2006, this case had the maximum wind speed (33.3 $\mathrm{m \cdot s^{-1}}$), the lowest air temperature (−16.1 ℃), the minimum visibility (<10 m), and the longest duration (17 h). Using the station-based meteorological observations and NCEP global tropospheric analysis data, the characteristics of this storm are discussed in this paper.

2 Surface and upper-level synoptic situation

As shown in Figure 1, the Antarctic cold high was very strong; its ridge extended northward controlling the whole Antarctic Peninsula and most part of the Bellingshausen Sea and Weddell Sea.

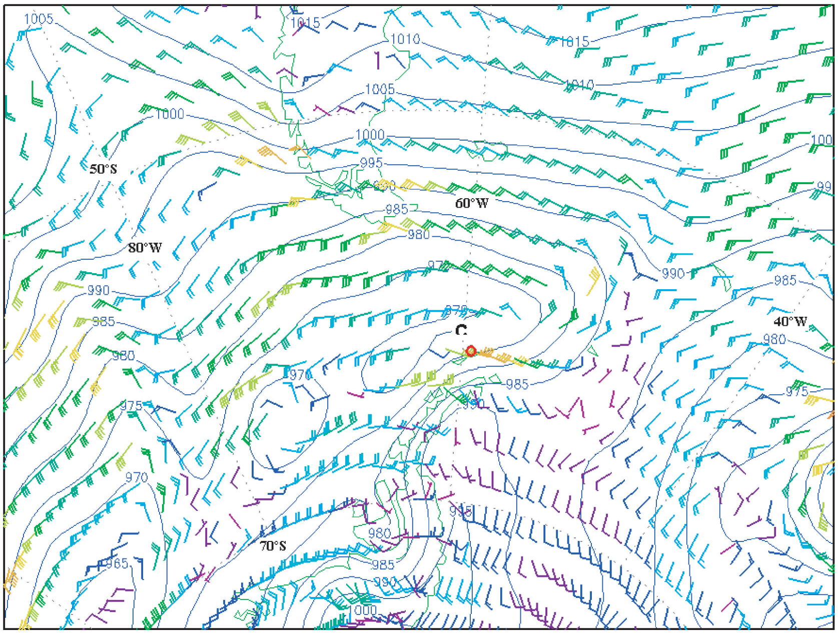


Fig. 1 Sea-level pressure and surface winds over the Antarctic Peninsula and the surrounding areas at 09:00 on August 29th, 2006; the red circle indicates the position of the GWS and the black "C" indicates the position of the cyclone center.

The South America high and South Pacific and South Atlantic subtropical highs centered north of 30°S were relatively weak. A synoptic-scale cyclone，centered in the Bellingshausen Sea with central pressure of 964 hPa，was blocked when moving eastward along 65°S，and then turned east-northeast under the guidance of the subtropical ridge（Fig. 2）. A mesoscale cyclone with central pressure of 970 hPa was separated from the front of the synoptic cyclone on the morning of 20th August，which can be found from the clear spiral clouds in the satellite image. The newly formed cyclone passed the northern tip of the Antarctic Peninsula quickly at a speed of 60-70 km • h^{-1}. The Antarctic cold high then regained control of the Antarctic Peninsula. The synoptic situation of a high in the south and a low in the north lasted about 30 hours. Circulation at the 850 hPa level was similar；i. e.，the Antarctic cold high extended northward and controlled the Antarctic Peninsula region，and there was a clear pattern of a high in the south and low in the north.

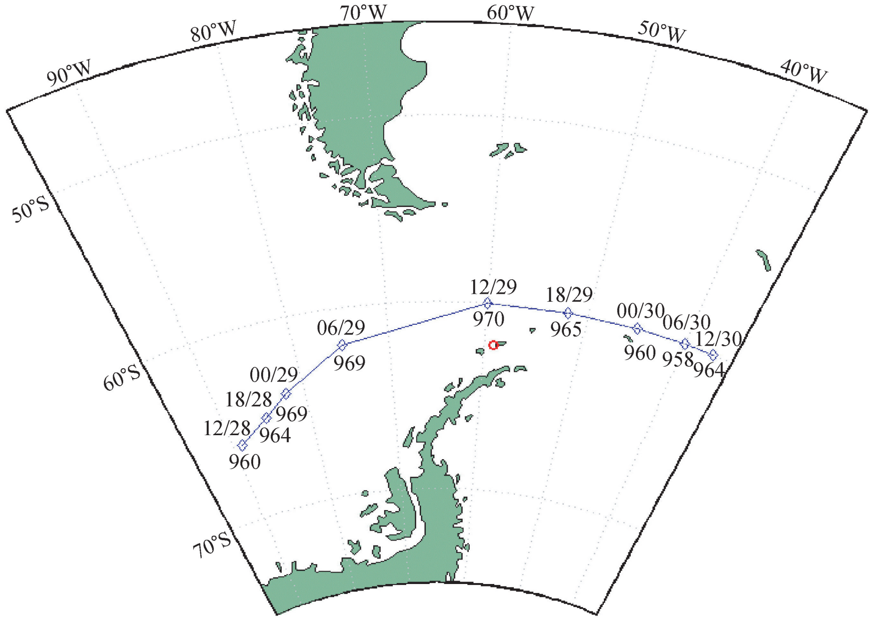


Fig. 2 Path and central air pressure of the cyclone（units：hPa）.

At the 500 hPa level，the center of the Antarctic polar vortex moved to western Antarctica from 00：00 on August 29th，gradually strengthened，and reached maximum intensity at 15：00 while centered at 76°S and having potential height of 468 gpm. Meanwhile，a cold trough extended northward，controlling the central and western South Atlantic. Associated with the surface cyclone，there was a vortex at the 500 hPa level with the height of its center less than 488 gpm（Fig. 3）. It is seen that the cyclone，extending from the surface to a high level，was a relatively deep system. In contrast，the Antarctic high was relatively shallow.

3 Surface meteorological elements

3.1 Air pressure and wind

The air pressure and wind speed fluctuated greatly as the cyclone passed; air pressure began to fall rapidly from 11:00 on August 28th, reached its minimum of 972.2 hPa at 08:00 on August 29th, and then began to rise rapidly (Fig. 4). There were northerly winds at the GWS before the cyclone passed, and the wind speed began to increase from 12:00 with the cyclone located to the south (65°S). As the cyclone turned east-northeast and passed north of the GWS gradually, the wind turned east-northeast from 22:00 on August 28th, sped up and reached a maximum of 26.3 $m \cdot s^{-1}$ (2 minute average; peak value of 33.3 $m \cdot s^{-1}$) at 08:00 on August 29th, and then slowed gradually.

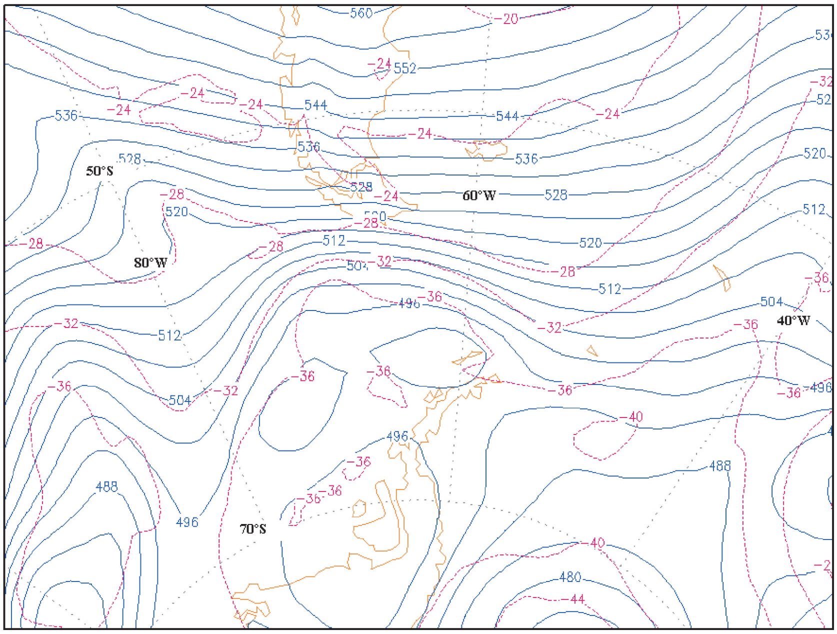


Fig. 3 500 hPa heights (blue lines) and temperature (red dotted lines) over the Antarctic Peninsula and the surrounding areas at 15:00, August 29th, 2006 (units: gpm).

The rapid change in air pressure directly reflected the cyclone quickly passing the northern tip of the Antarctic Peninsula and then the Antarctic cold high controlling the peninsula once again. The mesoscale cyclone, which moved eastward north of the GWS, together with the cold high in the Weddell Sea, formed the synoptic pattern of a high in the south and a low in the north. The GWS, located in the area of the most dense pressure gradients between the high and low pressure centers, was subject to strong winds. The rates of change in air pressure and wind speed were rather consistent, and there was a significant negative correlation between them.

3.2 Air temperature, humidity and snowfall

Both the air temperature and relative humidity underwent a U-shaped change; i.e., a substantial decline first, then small fluctuations, and finally a significant rise (Fig. 4). These changes are due to Antarctic ice shelves extending northward in winter and the sea ice of the Weddell Sea reaching north of 60°S. In this situation, King George Island is almost connected with the Antarctic Peninsula by sea ice, and thus, katabatic winds from the cold Antarctic plateau reach the GWS along the eastern side of the Antarctic Peninsula high ridge[7]. Easterly winds produced by a cyclone and Antarctic cold high are partially composed of katabatic winds, and contribute to the decline in temperature and humidity. As the cyclone moves away, the wind decreases and the air temperature rises sharply.

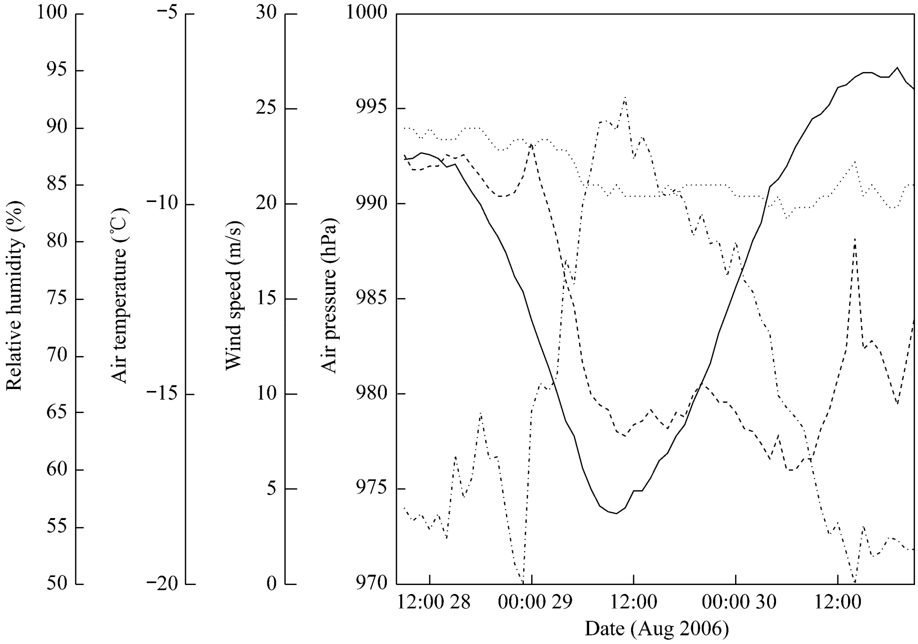


Fig. 4 Time series of surface meteorology elements observed at the GWS. Pressure: solid line; Temperature: long dashed line; Wind speed: dashedline; Relative humidity: dotted line.

There was intermittent light snow and wind-blown snow at 14:00 on August 28th, and the intensity began to increase rapidly since 02:00 on August 29th. A snowstorm formed and strengthened as the snow accumulated on the ground and wind speed increased. The precipitation measured between 02:00 and 18:00 was 10.5 mm; in particular, the amount between 02:00 and 08:00 was as high as 7.2 mm. Because much snow is blown away by strong winds, it should be pointed out that snowfall measurements during a storm are not reliable, and the actual precipitation may be much greater than the value measured. The snowstorm weakened and there was only wind-blown snow at 19:00. As the snowfall intensity decreased, the snowstorm tended to weaken and finally stopped.

According to changes in the meteorological elements, the snowstorm can be divided into two phases: (1) a forming and strengthening phase associated with significant decreases in air pressure, temperature and humidity and a rapid increase in wind speed before 08:00 on August 29th and (2) a maintaining and weakening phase, accompanied by a rapid increase in air pressure, a decrease in wind speed and maintenance of low temperature and humidity.

4 Vertical and horizontal atmospheric structure

Based on cold/warm advection and vapor conditions, atmospheric stratification stability, divergence and vorticity, vertical and horizontal winds during the studied event are analyzed as follows.

4.1 *Cold/warm advection and vapor conditions*

A nearly-saturated vapor layer appeared at 900-800 hPa at 15:00 on August 28th, thickened gradually, and extended to 400 hPa by the morning of August 29th. It is seen from the 1000-500 hPa thickness field that the upper level over the GWS was the crossing point of strong warm advection from the northwest and strong cold advection from the south. The GWS was simply in a strong northeast-southwest vapor convergence zone (Fig. 5). The convergence zone extended from the surface layer to 400 hPa, and there was also a vapor divergence zone with similar direction in the north of the convergence zone, indicating that the warm vapor was coming from the low-latitude ocean. High-level warm advection from low latitudes to the GWS brought a large amount of moisture, and the meeting of the cold and warm advections led to much condensation of the moisture, resulting in heavy snow. With the cyclone moving eastward, the saturated layer began to disappear from the top, and the relative humidity decreased significantly.

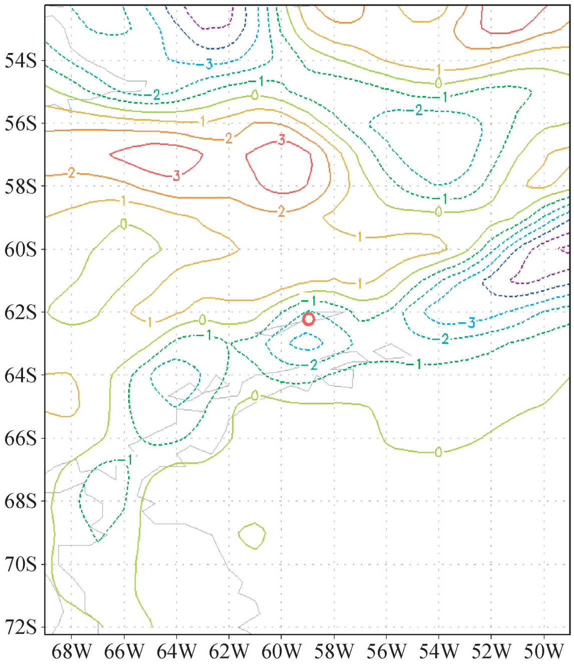


Fig. 5 Moisture flux divergence at 800 hPa at 03:00 on August 29th (units: 10^{-5} g • hPa^{-1} • s^{-1} • m^{-2}).

4.2 *Atmospheric stability*

There was an obvious inversion layer from 09:00 on August 29th that strengthened gradually, moved downward, and reached its maximum in intensity on the evening of August 29th (Fig. 6), indicating that the near-surface layer became more stable as the cyclone moved eastward. There was a significant low-level temperature inversion during the maintenance phase (09:00-19:00 on August 29th). The role of the low-level temperature inversion layer will be further discussed later.

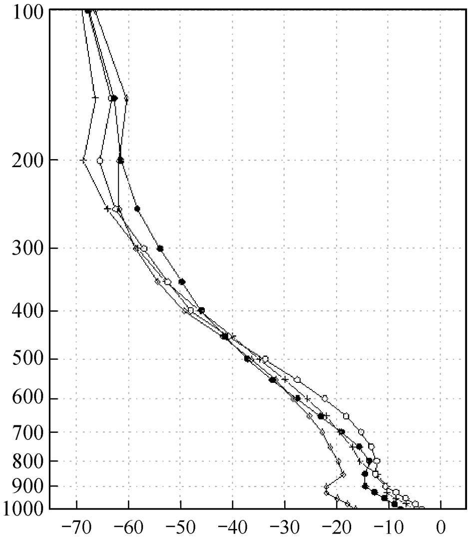
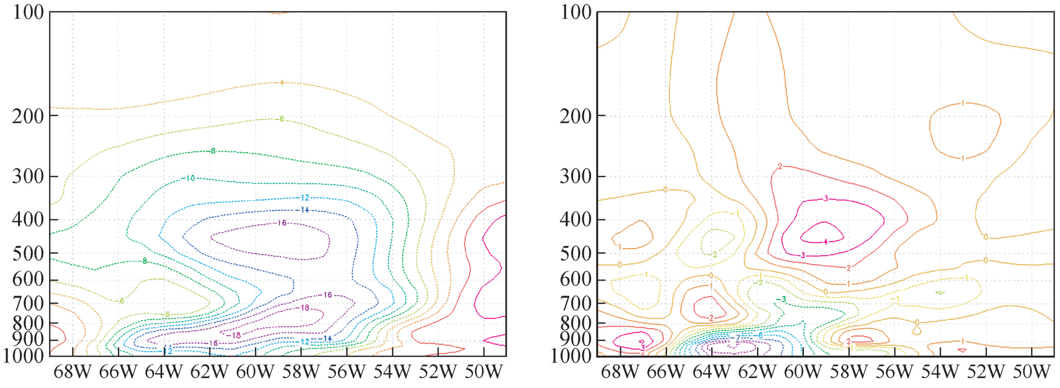


Fig. 6 Vertical profiles of air temperature at the GWS determined from NCEP analysis data. The abscissa indicates air temperature(°C) and the ordinate indicates air pressure (hPa); ×: 15:00 on August 28th, ○: 03:00 on August 29th, ●: 09:00 on August 29th, ◆: 21:00 on August 29th.

4.3 *Vertical vorticity, horizontal divergence, and atmospheric vertical motion*

It is seen from Figure 7a that the cyclone was a relatively deep system. Cyclonic vorticity (negative in the Southern Hemisphere) extended from the surface to 200 hPa; negative vorticity was centered at 800 hPa and had intensity of approximately $2\times10^{-4}\ \mathrm{s}^{-1}$. A positive vorticity center appeared near the surface soon after the cyclone moved away. There was simultaneous strong low-level convergence and high-level divergence that reached maximum intensity on the morning of August 29th. Taking the situation at 03:00 on August 29th for example, there was a convergence from the surface to 600 hPa, with the maximum intensity of $-1.2\times10^{-4}\ \mathrm{s}^{-1}$ at 900 hPa, and there was a divergence above 600 hPa, with the maximum intensity of $-5\times10^{-5}\ \mathrm{s}^{-1}$ at 400 hPa (Fig. 7 b). Strong convergence at low level and strong divergence at high level were favorable to heavy snowfall, resulting in a strengthening snowstorm. As the cyclone moved eastward, the vertical structure of the "convergence at low level and divergence at high level" system weakened rapidly, and there was a divergence at the low level of the GWS by the afternoon of August 29th.

There were also characteristics of vertical atmospheric movement. The weak rising current dominated the layer from the surface to 500 hPa on the afternoon of August 28th; as the cyclone moved closer, the vertical velocity increased significantly and was greatest on the morning of August 29th. The vertical uplift even extended from near the surface to 300 hPa, with the maximum intensity of more than -1.2 $\mathrm{hPa \cdot s^{-1}}$ at 700 hPa. After the cyclone left, uplift in the lower atmosphere weakened rapidly; for example, the falling rate reached 0.4 $\mathrm{hPa \cdot s^{-1}}$ at 15:00 on August 29th.



(a) (b)

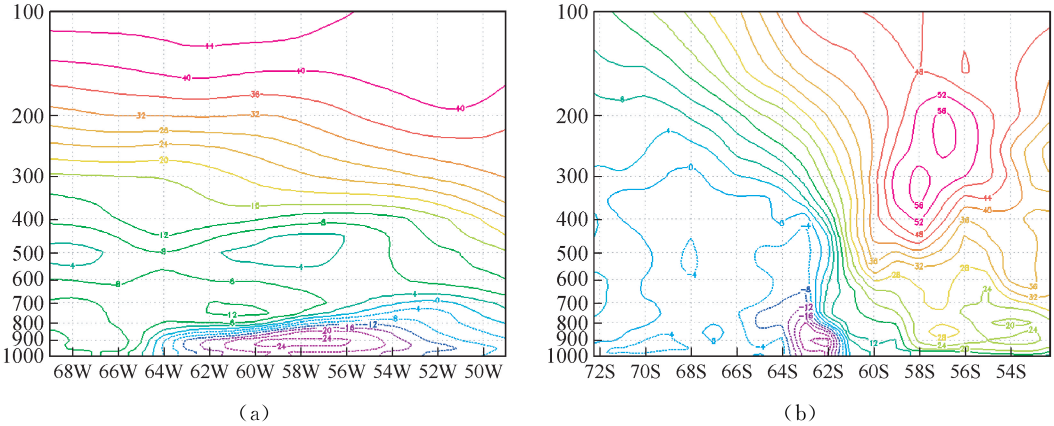
Fig. 7 Vertical cross sections of vertical vorticity and horizontal divergence along 62 °S at 03:00, August 29th (units: 10^{-5} $\mathrm{s^{-1}}$).

Analyses of vorticity, divergence and vertical motion show that the deep cyclonic vorticity at middle and low levels, divergence at high level and convergence at low level and the intense vertical uplift strongly mixed high-level warm/moist air and low-level cold/dry air, leading to heavy snowfall at the GWS and thus a snowstorm. With the cyclone moving away, the convergence at low level and uplifting motion decreased rapidly, the structure of the cold air-mass at low level and warm air-mass at high level resulted in the development of an inversion layer, and atmospheric stratification became more stable. It is presumed that the inversion layer may play an important role in the maintenance phase, in that it blocks vertical exchange between high and low levels. The lower atmospheric motion being limited to the horizontal is helpful in increasing horizontal wind speeds. Meanwhile, the inversion layer limits the upward transport of snow, snow is concentrated in the lower atmosphere, and visibility decreases rapidly, which is favorable for the maintenance of the snowstorm[7].

4.4 *Horizontal wind*

Analyzing the distribution of the horizontal winds at 09:00 on August 29th, it is seen that zonal wind was overwhelmingly dominant. An easterly wind prevailed from the surface to 800 hPa, and wind speed increased gradually from the surface to 900 hPa. The easterly jet axis was located at 900 hPa, and the maximum wind speed was near 30 $\mathrm{m \cdot s^{-1}}$. The strongest vertical wind shear was at 900-800 hPa (Fig. 8a). Westerly winds prevailed north of 61°S, and easterly winds prevailed to the south;

the strongest wind shear was at 62°-61°S (Fig. 8b). In the case of the meridional wind component, there was a weak northerly near the surface. The higher the level was, the lower the speed became, and the wind direction turned south at 900 hPa. The wind speed then increased, reaching a maximum at 800 hPa (about 14 $m \cdot s^{-1}$), after which it decreased.



(a)

(b)

Fig. 8 Vertical cross sections of zonal wind speeds at 09:00, August 29th, 2006 ($m \cdot s^{-1}$). (a) along latitude 62°S and (b) along longitude 59°W.

The vertical distribution of the horizontal wind reflected the synoptic pattern of a high in the south and a low in the north. Cyclones to the north of the GWS triggered the cold air over the Antarctic continent, and intense pressure gradients brought strong easterly winds, accompanied by a sharp reduction in air temperature and humidity. There was no southern high but there was a northern low above 800 hPa, where a warm and moist stream dominated. An inversion layer, accompanied by the storm, was determined by the air-mass structure of cold air at low level and warm air at high level.

To review the studied storm, we briefly describe its creation, development, maintenance and dissipation. First, the establishment of a high in the south and low in the north brought moist/ warm advection at high level and dry/cold advection at low level. The strong low-level convergence and high-level divergence, together with vertical motion, fully mixed the warm and cold air. Heavy snowfall resulted from the supply of moisture from the low-latitude ocean. As the cyclone moved away, low-level convergence and vertical movement weakened rapidly, the vertical structure of the air mass further developed low-level inversion, and the atmospheric stratification became more stable. The intensity of the storm thus decreased only gradually. With a lack of sustained snowfall or snow transportation, the storm finally stopped.

5 Conclusion

A snowstorm was discussed in terms of surface and upper-level synoptic patterns, meteorological elements, and horizontal and vertical atmospheric structure.

The easterly gale triggered by the pattern of a high in the south and a low in the north was essential to the development of the storm. The dynamic factors responsible for the snowstorm were high-level warm advection providing sufficient moisture, the air mass structure of warm air at high level and cold air at low level, and strong uplift. The inversion at low level may be favorable for the development and maintenance of the snowstorm.

The storm lasted for 17 hours owing to the accumulation of fresh snow before the gale developed, heavy snowfall during the storm, and snow transported by easterly winds providing sufficient snow. Therefore, to forecast a snowstorm, the gale and accumulation of fresh snow and the horizontal and vertical atmospheric structure should be taken into account to determine the scope and intensity of snowfall. The possibility of occurrence, intensity and duration of the snowstorm can then be predicted. It should be noted that the discussion here is only for one case, and further numerical modeling and diagnostic study are expected in an effort to explain the physical mechanism of Antarctic snowstorms.

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