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Seasonal variation of air transport in the Antarctic and Atmospheric Circulation in 1997

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Abstract: To better understand how present and past climates at Syowa Station, Antarctica relate to climate elsewhere, we analyzed the tropospheric air transport to Syowa Station for the year 1997 using a dataset from the European Centre for Medium Range Weather Forecasts (ECMWF). The five-day trajectories of the air parcels were estimated and analyzed. In the middle troposphere in winter, air parcels were usually from the lower troposphere over the Atlantic. However, in January, most of the air parcels came from latitudes higher than 60°S. The trajectories had little vertical motion and were associated with a low pressure system that forms along the coastal region of Antarctica only in summer. In the lower troposphere, trajectories could be classified as originating in one of three regions: the Southern Ocean, the continental interior, and the east coast. In contrast to the middle troposphere, air parcels from the Southern Ocean had the lowest frequency, irrespective of the time of year. This is partially due to a low pressure system that blocks air parcels from outside the continent. Most trajectories are affected by the drainage flow. An amplified quasi-stationary planetary wave for September to November and a blocking circulation in June make trajectories pass over Antarctica.

key words: trajectory, Syowa Station, polar vortex, planetary wave

1. Introduction

The Antarctic ice sheet consists of water transported through the atmosphere and then deposited at the surface (*e.g.*, Giovinetto *et al.*, 1997). Concentrations of minor atmospheric constituents, including greenhouse gases and aerosols that are recognized as strong climate forcing factors, are highly influenced by the long-range transport to Syowa Station (Morimoto *et al.*, 2003; Hara *et al.*, 2004). However, little is known about this air transport. Moreover, to completely interpret the analyses of ice cores from the region, we need more knowledge about the transport of water vapor and other minor constituents to the region.

The transport route of air parcels to the Antarctic region has been studied using trajectory analysis. Harris (1992) showed some mid-tropospheric flow patterns for the South Pole during 1985–1989. Using snowfall signals detected in an ice core, Reijimer *et al*. (2002) estimated the origins of the water vapor coming to the Antarctic continent using trajectory analysis for five locations in Antarctica (Vostok, Byrd, Dome F, Dome C, and DML05). The results showed the typical flow pattern and the origins of the water vapor. Murayama *et al*. (1998) examined the transport of air with high O_3 mixing ratios at Syowa Station using 3-D trajectory analysis. They suggested that the main transport path depended on the season, such that descending motion within the polar vortex occurred in spring and autumn, whereas transport from the circumpolar region was important in summer.

Air parcel trajectories are controlled by atmospheric flow patterns that vary daily, seasonally, and yearly. The average westerly wind between 50° and 65°S peaks in March and September (Van Loon, 1967). In summer and winter, cyclonic activity generally decreases over the ocean at higher latitudes, the major pressure gradient appears further north, and westerly winds between 50° and 65°S weaken.

A stationary planetary wave of wave number 1, hereafter WN1, exists all year round. The amplitude at 500 hPa peaks in the subpolar regions with a ridge in the Pacific and a trough in the Atlantic (Van Loon *et al*., 1972). The major features of the observed stationary eddy fields remain the same between summer and winter in middle and high latitudes, although the amplitude is larger in winter than in summer (Kitoh *et al*., 1990). These stationary planetary waves induce meridional transport of air over large scales such as that between the polar region and midlatitudes. Moreover, these waves influence the storm tracks that can mix air over synoptic scales.

Air parcels coming to Syowa Station are likely influenced by cyclones that pass through the middle latitudes over the South Atlantic Ocean and the Southern Ocean. At Syowa Station, synoptic-scale disturbances typically cause more than 20 blizzards per year (*e.g*., Higashijima *et al*., 2003). Also, at an inland station, Hirasawa *et al*. (2000) showed that a blocking event could bring a large amount of air into Antarctica that normally would not come.

The purpose of the present study is to describe the seasonal changes of air transport to Syowa Station in the lower and middle troposphere. We also examine how the atmospheric circulation causes seasonal variations in the air transport.

2. Data and analysis

We used the 3-D backward trajectory analysis developed by Sato and Tomikawa (Yamanouchi *et al*., 2004) for air parcels arriving at Syowa Station (69°00′S, 39°35′E) in 1997. Trajectories in 16 layers were calculated 5 days back because going further back in time would have large uncertainties. These 16 layers each covered 50 hPa between 100 and 850 hPa. Each trajectory calculation started at 12 UTC and the time step was 1 hour. The objective analysis atmospheric data for this study were the Tropical Ocean and Global Atmosphere (TOGA) Level III atmospheric data provided by the European Centre for Medium Range Weather Forecasts (ECMWF). The data are 4-times daily on a 2.5° grid at 12 mandatory pressure surfaces. Bromwich *et al*.

(1995) compared ECMWF analyses to East Antarctic rawinsondes and numerical analyses. They found that the ECMWF analysis best reproduced sounding values for the moisture flux at each level. As one purpose of our study was to determine the vapor circulation in the Antarctic, we chose to use the ECMWF analysis.

3. Seasonal variation in the middle troposphere

3.1. Trajectory analysis

We first discuss the monthly changes in the 5-day trajectories that reach a height of 500 hPa over Syowa Station (Fig. 1). In January, most of the air parcel sources are distributed in latitudes higher than 60°S of the Atlantic Ocean sector. Figure 2 shows the monthly averaged transport distance of air parcels in the middle and lower troposphere. Among all months, the transport distance in January is the shortest. From February to June, a high frequency of trajectories spread into the area between 40° and 60°S over the Atlantic Ocean. The lengths of the trajectories gradually become longer through this duration. After June, the high frequency over the Atlantic Ocean is maintained until November.

In June, several trajectories originate north of 40°S over the Indian Ocean, and pass through inland Antarctica. These trajectories are associated with a blocking event reported by Hirasawa *et al*. (2000). Also in July, there are trajectories passing over the Indian Ocean that are associated with a developed synoptic-scale disturbance in the Antarctic region.

In September, October, and November, many trajectories meander and pass over the Antarctic continent. The trajectory lengths gradually decrease from September to December. In December, the air parcels come from the east, either from the continent or through the sector of the Indian Ocean in the Southern Ocean.

In January, most trajectories came to Syowa Station with little vertical motion, although a few trajectories came from the lower troposphere in middle latitudes (Fig. 1b). The latter trajectories came from the Indian Ocean in Fig. 1a. In July, on the other hand, a large number of trajectories come from the lower troposphere in middle latitudes (Fig. 1b). This feature is generally seen from February to November with large variation in altitude.

3.2. Geopotential height field at 500 hPa

In order to extract significant circulation patterns from the distribution of trajectories, monthly averaged geopotential height field is examined here. This field represents stationary circulation patterns and also indicates the activity of synoptic disturbances along the averaged westerly jet. Figure 3a shows the monthly averaged geopotential height at the 500 hPa level, hereafter Z500, in January and July. In January and July, Z500 decreases rapidly with latitude in middle latitudes, corresponding to strong westerly winds. The Z500 over Antarctica is different between the two months. In January, Z500 is low in the coastal region of the continent and relatively high over the interior. Syowa Station is exposed to moderate easterly winds that appear poleward of the low Z500 region. A large amount of air moves eastward on the northern side of the low Z500 region, turns southward, and then reaches Syowa Station

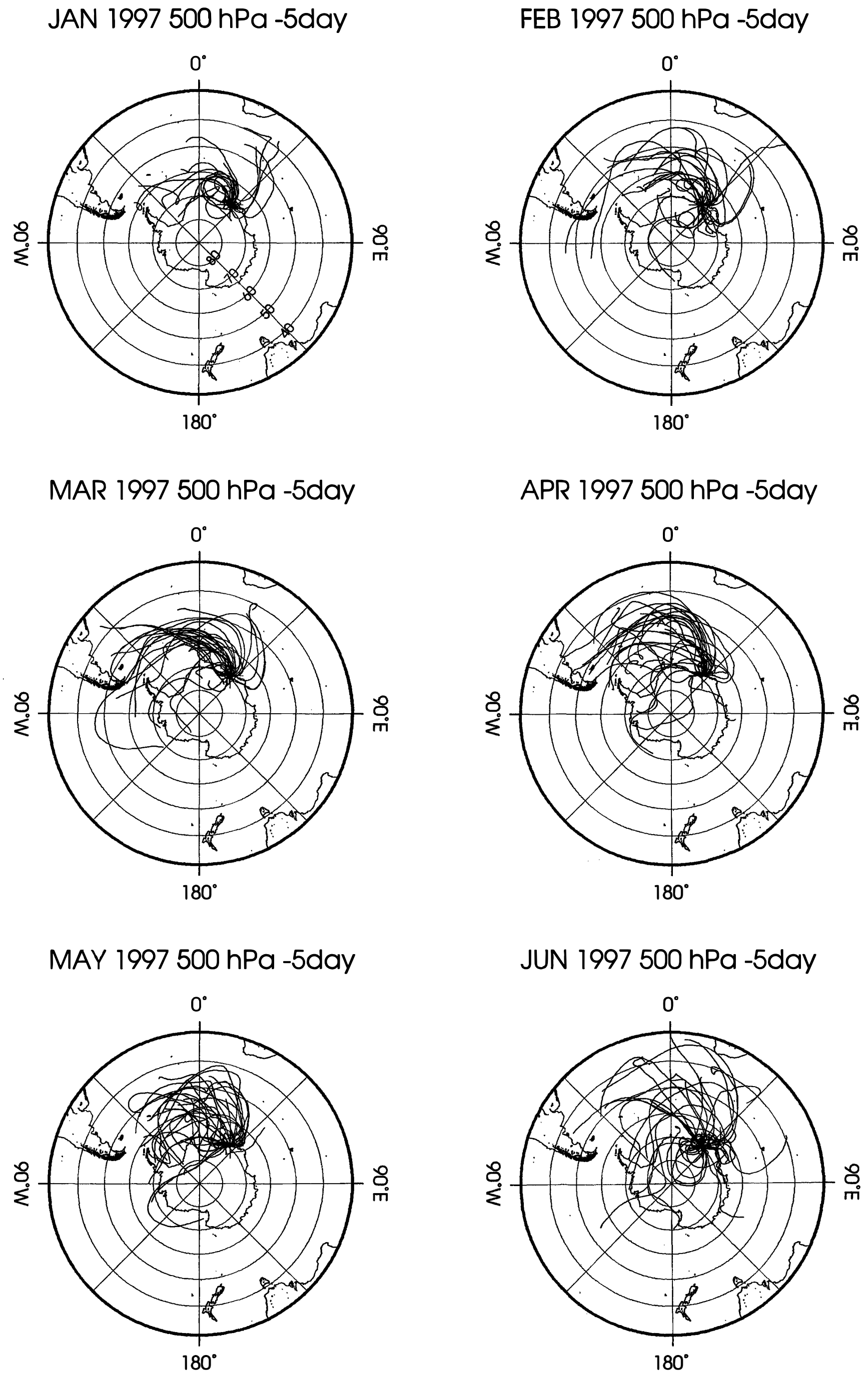


Fig. 1a. Horizontal distribution of backward trajectories that reached a height of 500 hPa over Syowa Station in 1997. Calculations ended either at 5 days or when a trajectory crossed a mountain or sea surface.

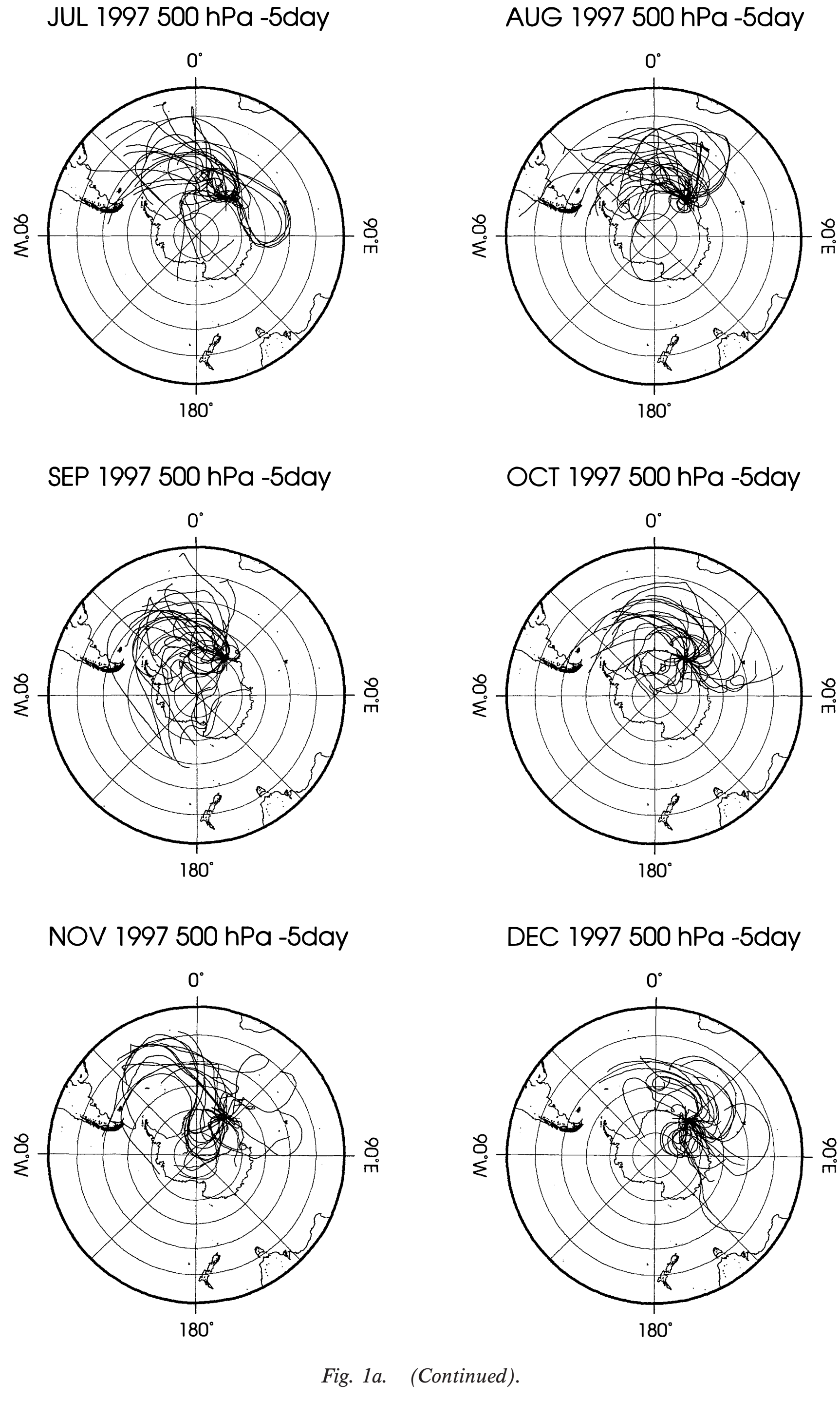


Fig. 1a. (Continued).

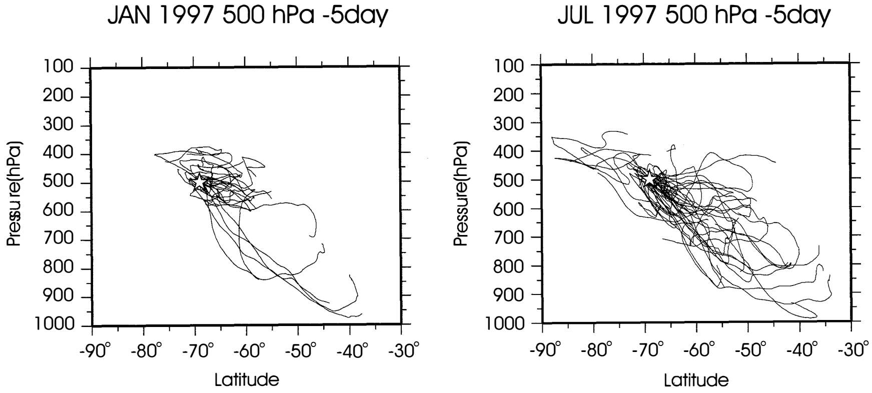


Fig. 1b. Vertical distribution of trajectories in (a) for January and July, 1997.

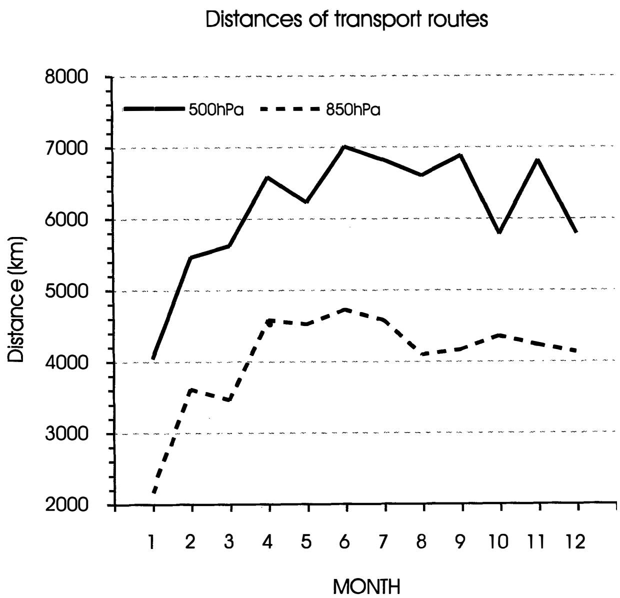
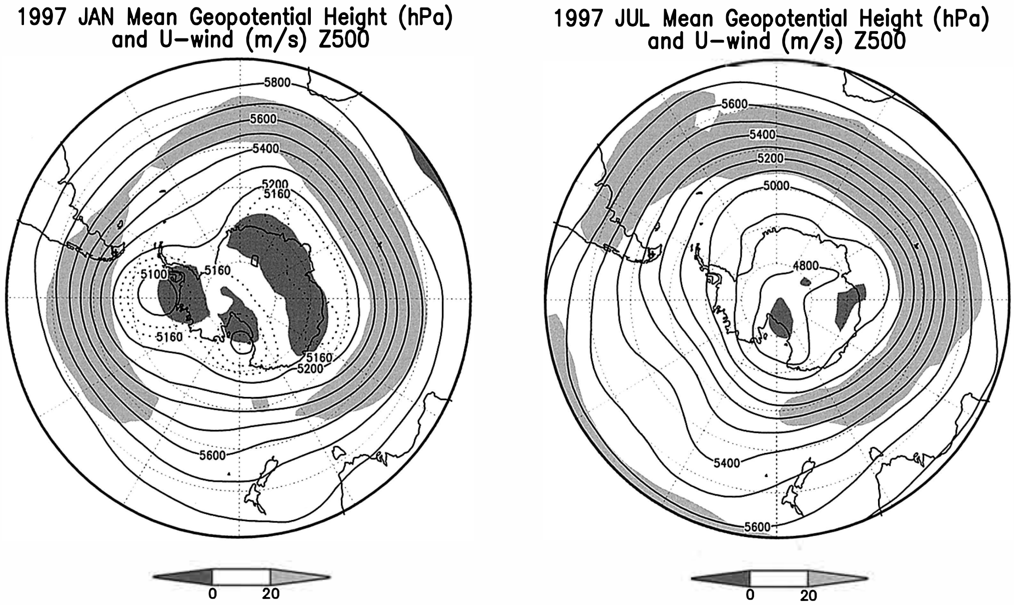


Fig. 2. Monthly average of the transport distance of air parcels for 5 days. The solid line is for trajectories that reached a height of 500 hPa over Syowa Station; the dotted line is for trajectories that reached 850 hPa.

from the east. Some trajectories are trapped by a low Z500 cell centered near 30°E and 65°S. These air parcels have little vertical motion. On the other hand, a few air parcels from the region south of Africa have originated in the lower troposphere in the strong westerly region.

In July, a center of low Z500 appears over Antarctica. Syowa Station is covered by the southernmost region of the circumpolar westerlies. Trajectories in July are concentrated around the center of the circumpolar westerlies in the Atlantic Ocean.

(a)



(b)

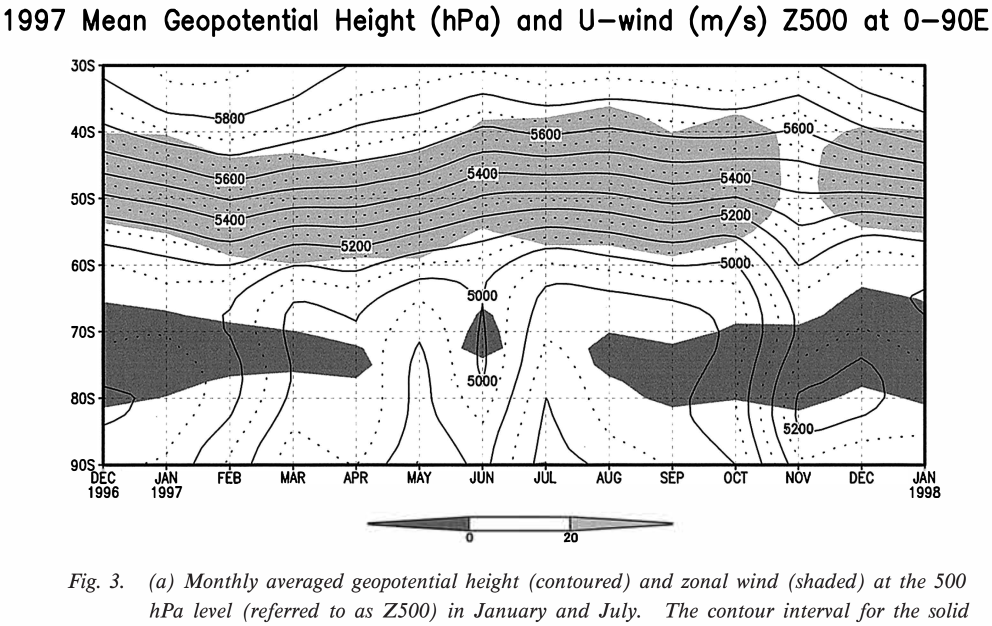


Fig. 3. (a) Monthly averaged geopotential height (contoured) and zonal wind (shaded) at the 500 hPa level (referred to as Z500) in January and July. The contour interval for the solid lines is 100 m. The lines for 5130 and 5160 m are dotted. Dark shading is easterly wind and light shading is westerly wind.

(b) Time-latitude section of the geopotential height (contoured) and zonal wind (shaded) of the 500 hPa level averaged between 0 and 90°E in 1997. The contour interval between adjacent solid lines in 100 m and the dotted lines are 50-m from the nearest solid line. Shading is the same as that in (a).

The daily Z500 weather maps (not shown here) showed that the air parcels came from the westerly wind zone to Syowa Station in association with synoptic-scale disturbances that develop in the circumpolar westerlies. Thus, the relevant air parcels at 500 hPa level over Syowa Station originated in the lower troposphere over the Atlantic Ocean.

Figure 3b shows a time-latitude section of Z500 averaged between 0° and 90°E. The Z500 minimum in the coastal region of the continent (60°–70°S) is relatively deep, especially in January and December. However, in December, a stronger gradient in the Z500 in the coastal region induces a stronger easterly wind than that in January. Hence, the trajectories from the east are more elongated in December than in January. In February and March, Z500 decreases in the polar region, and the low Z500 band disappears from around the continent. Under these conditions, the circumpolar westerlies influence the area around Syowa Station and there is an increasing number of trajectories from over the Atlantic. Later, from April to August, the southernmost part of the westerly wind zone (indicated by a gradient in Z500) just reaches the latitudes near 70°S, the latitude of Syowa Station (Fig. 3b). Consequently, in this duration, many trajectories originate in the westerly wind zone over the Atlantic.

The September to November period, on the other hand, is characterized by increasing Z500 in the polar region and a retreat of westerly wind from the coastal region. The temporal variation of the distribution of trajectories in this period is not the opposite of the situation in February and March, but instead shows an increase in the number of trajectories passing over Antarctica. This increase means that the meridional flow between the middle latitudes and Antarctica is stronger during this period. A similar situation occurs in June. The relationship between the atmospheric circulation and the trajectories in these periods is described in Section 5.

4. Seasonal variation in the lower troposphere

4.1. Trajectory analysis

In this section, we discuss the trajectories that reach a pressure level of 850 hPa, which correspond approximately to the boundary between the free atmosphere and the planetary boundary layer. Figure 4 is similar to Fig. 1 but is instead for 850 hPa. Throughout the year, trajectories at 850 hPa can be classified into one of three patterns: those coming from inland of Syowa Station in Antarctica (continental interior), those coming along the east coastal region (east coast), and those coming from the Southern Ocean, south of the Atlantic (south ocean). These are shown in Fig. 5a. We classified the trajectories into one of these areas according to the parcel's position two days before reaching Syowa Station. This classification indicates the direction, not the origin. Figure 5b shows the total number of air parcels for each area per month.

The continental interior generally has the highest number of parcels throughout the year, except for January and December, when the number for the east coast is highest. In January and July, almost all the trajectories from the east coast and the continental interior go downward along the continental surface (Fig. 4b). This indicates that drainage flow, that is, the Katabatic wind, has a large effect in the lower troposphere over Syowa Station. The relative amount of air coming over the south ocean is low for most of the year, except for March and June when it exceeds that from the east coast.

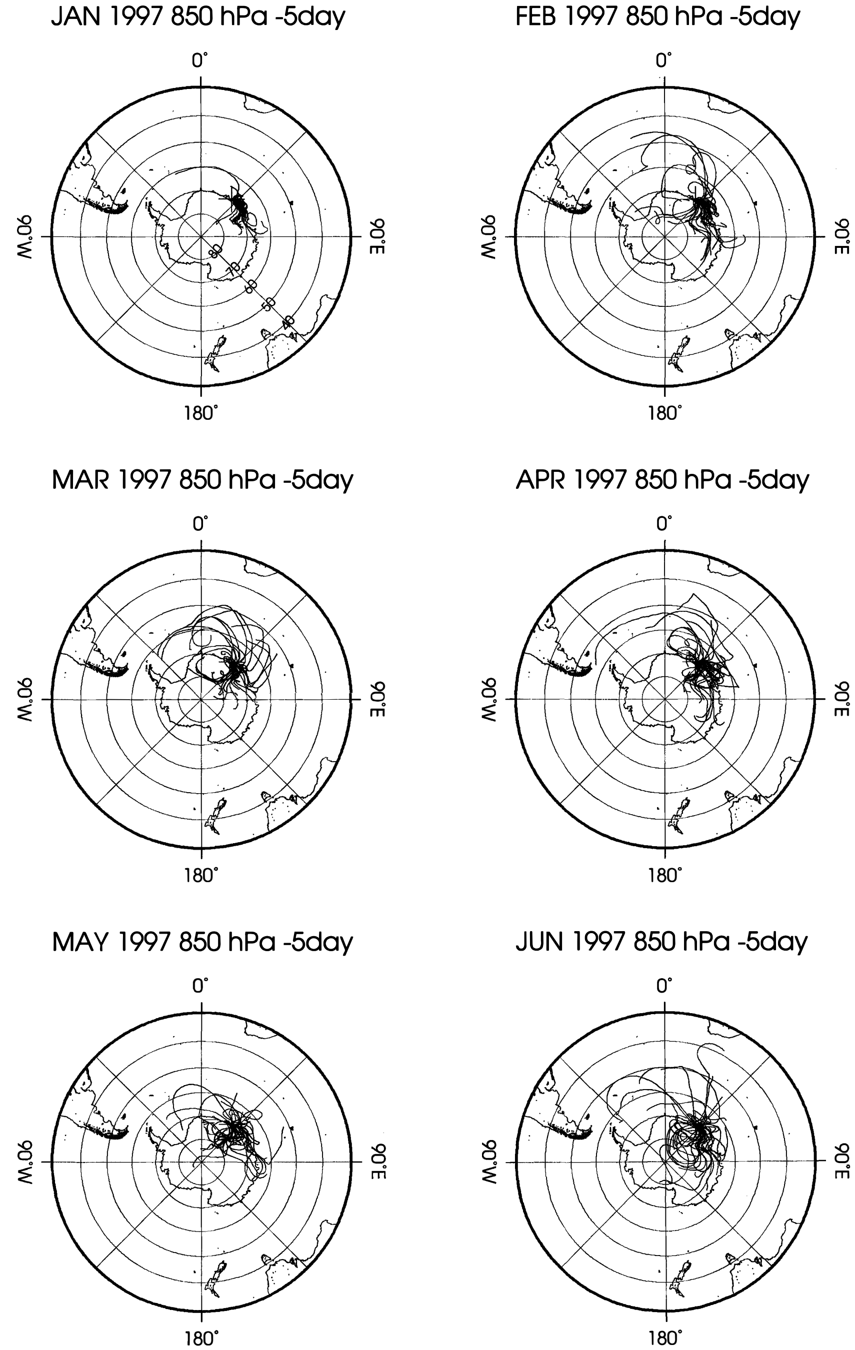


Fig. 4a. Horizontal distribution of backward trajectories that reached a height of 850 hPa over Syowa Station in 1997. Calculations ended either at 5 days or when a trajectory crossed a mountain or sea surface.

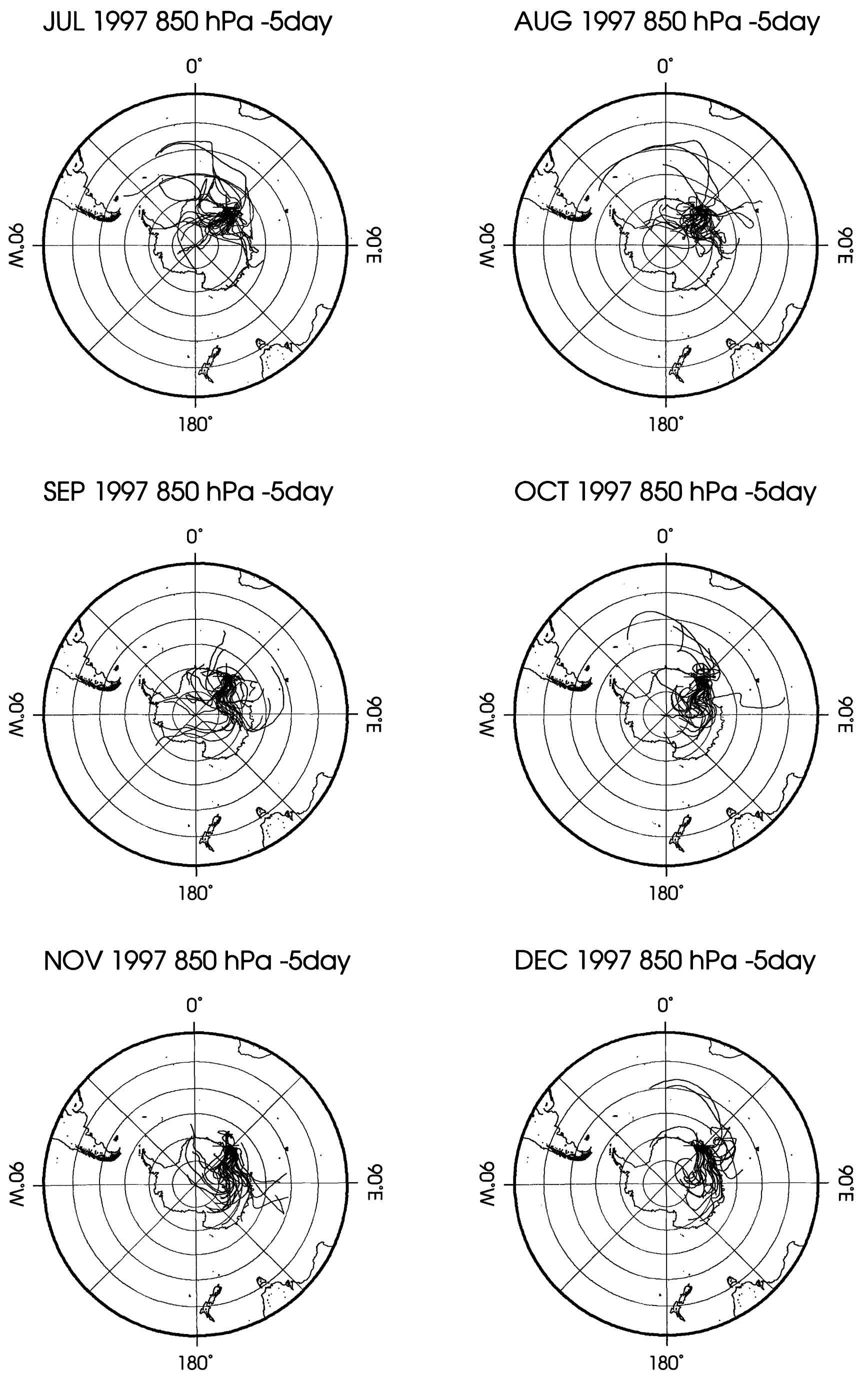


Fig. 4a. (Continued).

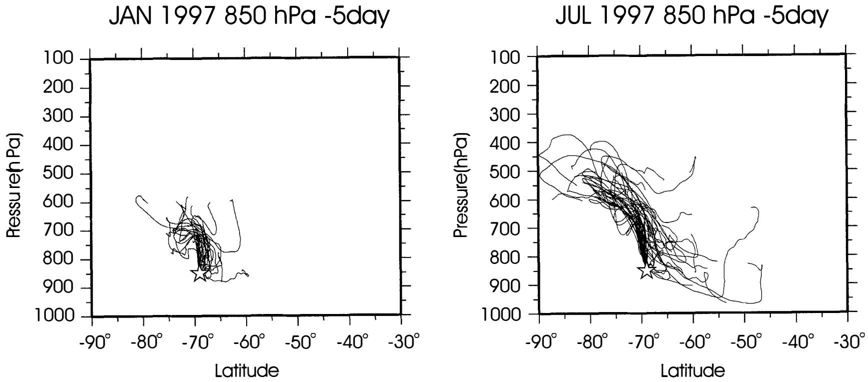


Fig. 4b. Vertical distribution of trajectories in (a) for January and July, 1997.

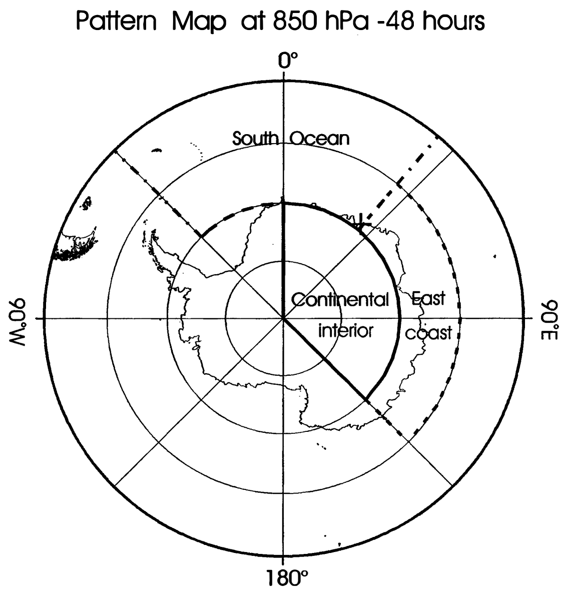


Fig. 5a. Map showing the three areas where air parcels had been two days before reaching Syowa Station (69°00′S, 39°35′E). The areas are the continental interior (70°–90°S, 0°–135°E), east coast (60°–70°S, 40°–135°E), and south ocean (50°–70°S, 45°W–40°E).

In this case, most air parcels originate in the planetary boundary layer below the 850 hPa level.

4.2. Geopotential height field at 850 hPa

Figure 6a is similar to Fig. 3a, but is for Z850, the geopotential height of 850 hPa. The surface air pressure over most of the Antarctic continent is lower than 850 hPa because of its high elevation, and thus we do not show contours over Antarctica. In

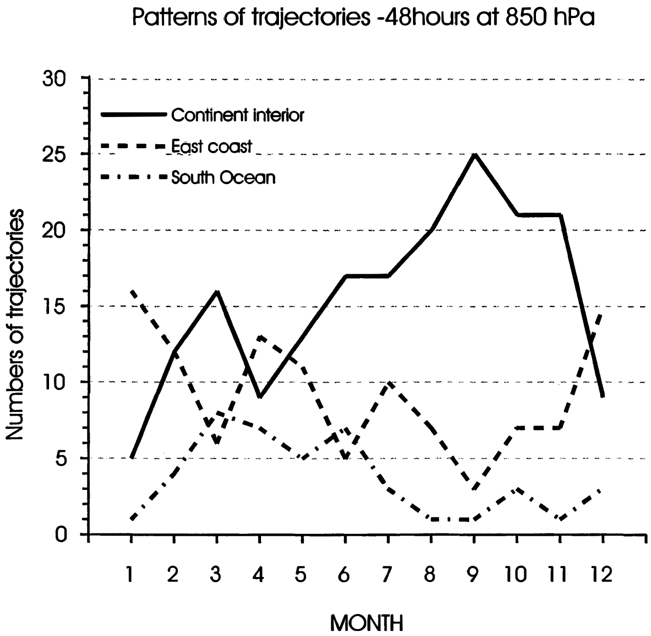


Fig. 5b. Monthly total number of air parcel positions for trajectories that reached a height of 850 hPa over Syowa Station. The solid line connects adjacent values for the continental interior area, the dotted line for the east coast, and the dashed line for the south ocean area.

January and July, a large gradient of Z850 exists at latitudes between 40° and 60°S. As this also occurs for Z500, this indicates that the westerly wind zone is deep in the troposphere at those latitudes. Both months have low Z850 values in the coastal region. Syowa Station is located to the south of the low Z850 region and thus is in an easterly wind zone. In July, there is also an intensified westerly wind at middle latitudes and an intensified easterly wind in the coastal region.

Figure 6b is similar to Fig. 3b but is for Z850. The band in the latitude range of 60°–70°S has low Z850 values throughout the year and is lowest in winter. The geopotential height gradient in Z850 is small around this band in January, which indicates that the easterly wind near and over Syowa Station is weak.

From March to June, the easterly wind on average near Syowa Station gradually becomes strong in association with a decrease in height of the low Z850 band. The deepening of the low Z850 band is also consistent with the southernmost part of the mean westerly wind shifting to the south of 65°S (*i.e.*, near the latitude of Syowa Station) in this period. This should be a situation in which air parcels reach Syowa Station from the westerly wind region. Although the height of the low Z850 band changes little in July and August, the area with a small gradient in the low Z850 band becomes wide in latitude. This situation keeps westerly winds away from Syowa Station; consequently, air parcels from the Atlantic Ocean do not arrive very often.

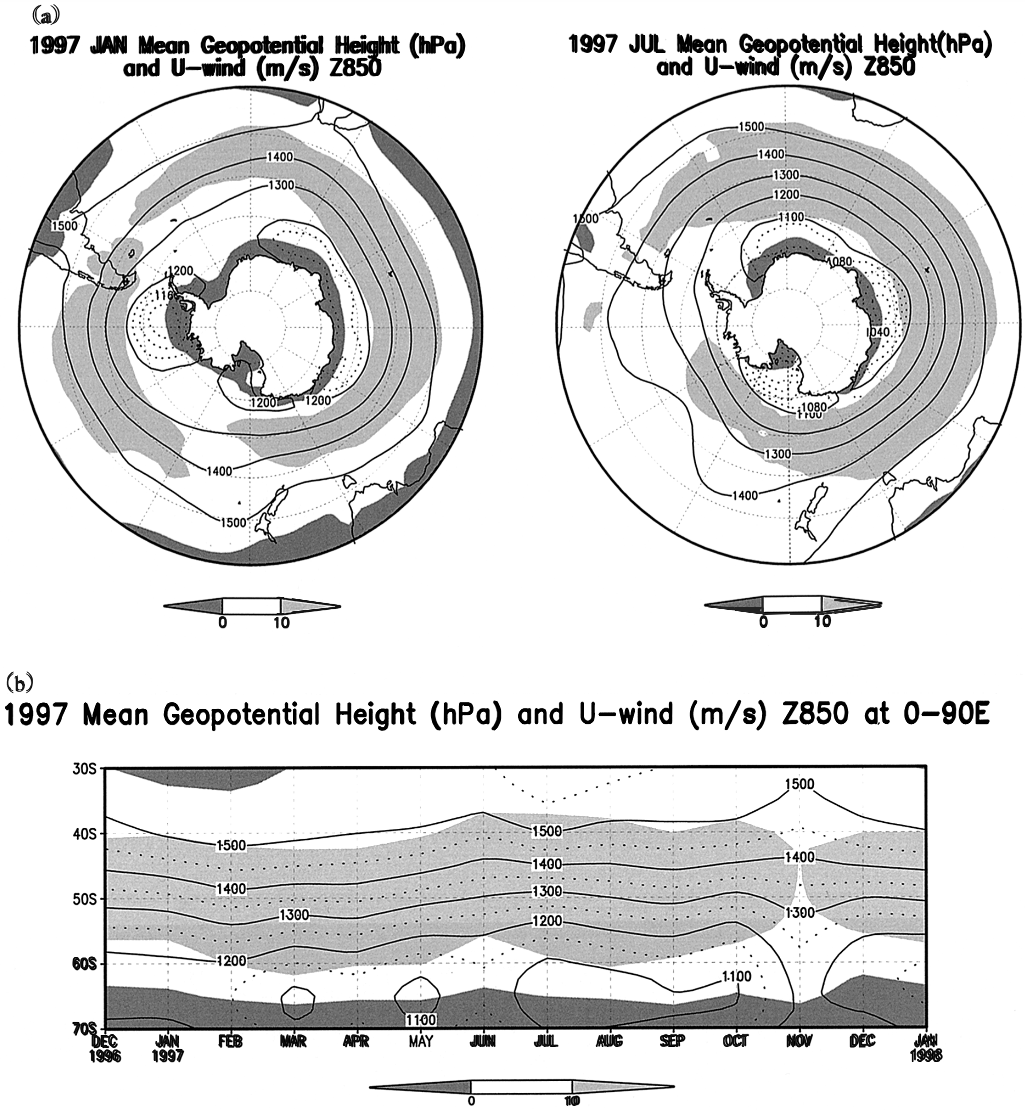


Fig. 6. (a) Monthly averaged geopotential height (contoured) and zonal wind (shaded) at the 850 hPa level (referred to as Z850) in January and July. For the solid lines, the contour interval is 100 m. Lines under 1200 m in January and under 1100 m in July are shown dotted and have a contour interval of 20 m. Dark shading is easterly wind and light shading is westerly wind.
(b) Time-latitude section of the geopotential height (contoured) and zonal wind (shaded) at the 850 hPa level averaged between 0 and 90°E in 1997. The contour interval between adjacent solid lines in 100 m and the dotted lines are 50-m from the nearest solid line. Shading is the same as that in (a).

5. Trajectories that pass over the Antarctic continent

5.1. Quasi-stationary planetary wave in spring

In this section, we focus on the atmospheric circulation patterns in spring (between September and November), which is when trajectories reach Syowa Station after passing over the inland Antarctic continent. To estimate the frequency of such trajectories, we calculate the residence times for the air parcels to be in the area from 70° to 90°S, which are indicated in percentage for the total time (120 hours). Figure 7 shows the monthly average residence times of trajectories starting in the middle (300 to 600 hPa) and the lower (650 to 850 hPa) troposphere. The residence time in the middle troposphere is roughly constant from February to August. It increases significantly in September and remains large through November. In the lower troposphere, the monthly variation in the residence time is similar to that for the middle troposphere, but the absolute values are about twice those of the middle troposphere. In December, the residence time in the lower troposphere decreases from that in November.

The monthly averaged Z500 for September shows a planetary wave of wave number 3, hereafter WN 3, with low pressure regions near 30° W, 90°E, and 150° W (Fig. 8). The planetary wave has an almost barotropic structure through the troposphere (not shown). Such a planetary wave of WN 3 does not dominate in January and July.

Figure 9 shows a time-longitude section of 31-day moving-average anomalies from the zonal mean of the geopotential height of Z500 between 55° and 65°S. The planetary wave of WN 1 dominates in these latitudes throughout the year, and the increment in the amplitude of the quasi-stationary planetary wave of WN 3 is found especially in September to November.

Fig. 7. Monthly average residence times for trajectories that began in the 300–600 hPa range (middle troposphere) and 650–850 hPa (lower troposphere) over Syowa Station.

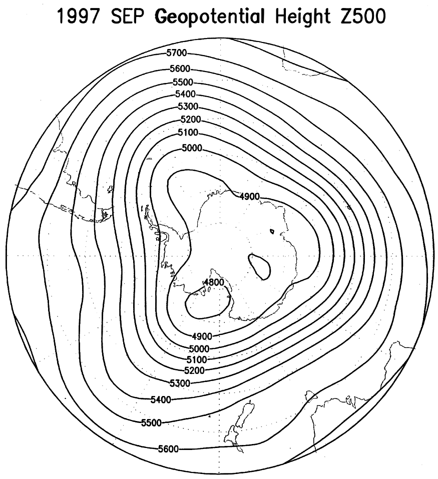


Fig. 8. Monthly averaged geopotential height at the 500 hPa level for September. The planetary wave shown has three low-pressure regions: near 30°W, 90°E, and 150°W.

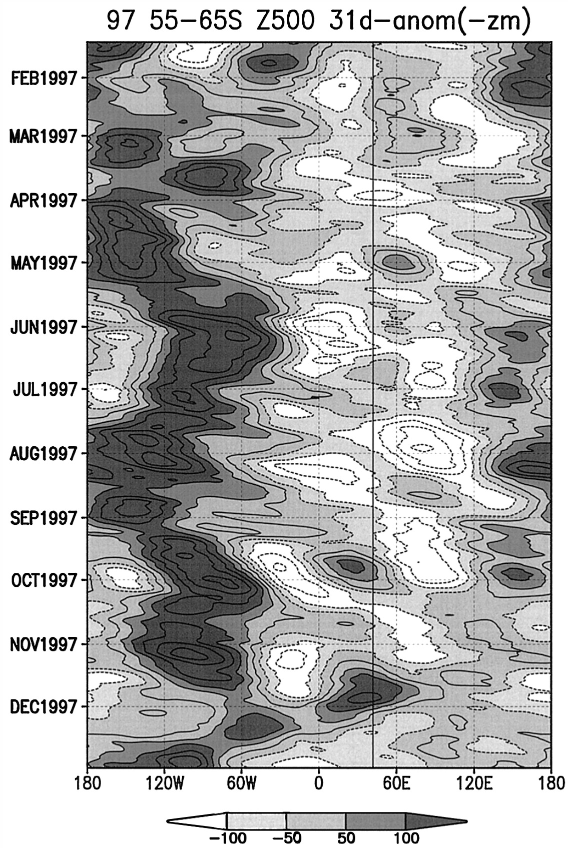


Fig. 9. Time-longitude section of 31-day moving-average anomalies from the zonal mean of the geopotential height at the 500 hPa level between 55° and 65°S. The solid lines are positive values; dotted lines are for negative values.

The flow associated with disturbances can cause mixing of air parcels between latitudes. To better understand the relationship between the trajectories and the flow generated by the planetary wave of WN 3, we analyzed the trajectories coming through the continent on 19 September when there is a clear planetary wave. Figure 10a shows three low-pressure regions near 30° W, 60° to 90°E, and 150° to 170° W. This feature occurs on all five days from the 15th to the 19th of September. Following the trajectory in Fig. 10a, the air parcel enters the continental interior through the eastern periphery of the trough at 60° to 90°E. The parcel comes to Syowa Station through the western periphery of the same trough after traveling over the continent. Many air parcels came to Syowa Station through the western periphery of the trough at 60° to 90°E, which comprises a quasi-stationary planetary wave of WN 3, whereas some air parcels enter into the continental interior through the eastern periphery of the trough at 30° W.

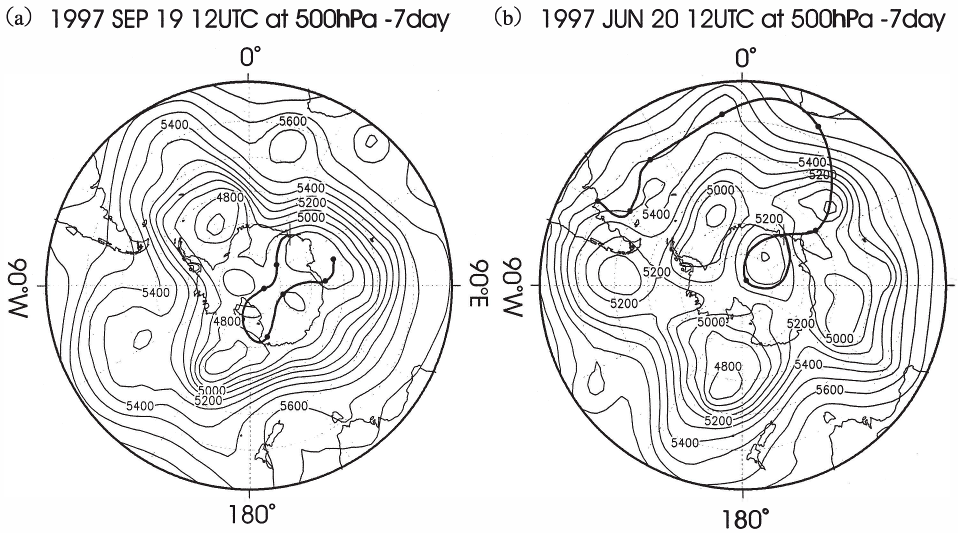


Fig. 10. *(a) The 7-day backward trajectory of a 19 September air parcel that reached a height of 500 hPa over Syowa Station. The trajectory began at 12 UTC. The dots were drawn for every 12 UTC (i.e., once per day). The geopotential height at the 500 hPa level on 19 September is shown by contours.*
(b) Same as that for (a) but for 20 June.

5.2. *Blocking in June*

A blocking event occurred on 20 June that altered the air parcel trajectory over Syowa Station. One trajectory is shown in Fig. 10b. The trajectory originates in the westerly wind zone, passes near Syowa Station on the western side of the blocking anticyclone, then enters into the continental interior, and finally circles back to the station on the eastern side of the anticyclone.

The position of Syowa Station relative to the circulation pattern is similar for both the planetary wave of WN 3 and the blocking, that is, there is a ridge to the west of Syowa Station and a trough to the east.

6. Summary

Using trajectory analysis, we examined the seasonal changes of air transport trajectories coming to Syowa Station in the middle and lower troposphere in 1997. In the middle troposphere, most air parcels came from the lower troposphere of the westerly wind region in middle latitudes throughout the year, except for January. In January, most air parcels came from latitudes higher than 60°S, where a low geopotential height band was located, and had little vertical motion, and consequently few air parcels came directly from the westerly region to Syowa Station. In the lower troposphere, trajectories were classified into three patterns: those coming from inland of Syowa Station (continental interior), those coming along the east coast region (east coast), and those coming from the Southern Ocean, south of the Atlantic (south ocean).

Air parcels from the Southern Ocean were the least common throughout the year, partially due to a low geopotential height band surrounding the continent similar to that at 500 hPa in January. Instead, trajectories were mainly from the east coast and continental interior. These trajectories are supposed to be associated with a drainage flow system (Katabatic wind) in the planetary boundary layer over Antarctica. These results are relevant to the origin of the stratified air over Syowa Station in winter. Namely, air in the middle troposphere comes from the lower troposphere in middle latitudes, whereas that in the lower troposphere comes from the middle troposphere over the continent. This result is relevant to the advection of concentrations of minor atmospheric constituents.

We also found that trajectories can pass through the continental interior when a blocking event develops over Antarctica or when the amplitude of a quasi-stationary planetary wave of WN 3 becomes relatively large. In this case, for the air parcels to come to Syowa Station from the continental interior, a ridge to the west of Syowa Station and a trough to the east must form. Then, the air parcels take a path between the ridge and trough.

We studied the seasonal variation of air transport to Syowa Station during 1997. It is not yet clear how these results apply to other years. To find out, we should study the climatology of the air transport for Syowa Station for at least 10 years. In particular, we need to better understand how the various planetary waves influence the trajectories on daily and seasonal timescales. In addition, we aim to find out more about the relation between these variable trajectories and the transport of water vapor and atmospheric minor constituents to Antarctic stations.

Acknowledgments

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