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TRANSPORT CHARACTERISTICS IN THE TROPOSPHERE AND LOWER STRATOSPHERE OF THE SOUTHERN HEMISPHERE

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Abstract: Trajectory analyses of air parcels for the Southern Hemisphere spring are performed with observed data during the period from September to December of 1982. It is found that the diffusivity at 60°S and poleward in the lower stractosphere is low during early spring. The diffusion in December is nearly homogeneous and turbulent in the lower stratosphere. Net advective motion is estimated following H. KIDA (J. Meteorol. Soc. Jpn., **61**, 171, 1983). In September at 50–100 mb, the net advective motion is upward in the polar region and downward at 50–60°S. This meridional cell is quite similar to the one proposed by K. K. TUNG *et al.* (Nature, **322**, 311, 1986) in both shape and magnitude. A sudden increase of ozone was observed at Syowa Station (69°S) on October 28, 1982. It is inferred from the backward trajectory analysis that this sudden ozone increase was primarily caused by a strong downward motion.

1. Introduction

Recently, the decreasing trend of total ozone amount over Antarctica has been reported by many authors (FARMAN *et al.*, 1985; STOLARSKI *et al.*, 1986; CHUBACHI and KAJIWARA, 1986). The rate of decrease is largest during the spring season, especially in October, while the decrease in other seasons is not clear. Namely, the total ozone amount over Antarctica in mid-winter shows little or small secular trend and its seasonal decrease during spring becomes remarkable in recent years (CHUBACHI, 1984; STOLARSKI *et al.*, 1986). In other words, the recent "ozone hole" has become deeper in spring. On the other hand, the ozone maximum observed at 50–60°S surrounding the "ozone hole" increases during spring, and the area weighted total ozone integral from 44°S to the pole does not show a seasonal decrease (STOLARSKI and SCHOEBERL, 1986). This fact suggests that the dynamical redistribution of ozone between middle-latitude and the polar region plays a major role during spring in the seasonal deepening of the "ozone hole". In the Arctic region, the springtime temporal variation of ozone does not show such decrease. Then, an interesting question arises, namely, how unique is the springtime Southern Hemisphere circulation in the lower stratosphere.

TUNG *et al.* (1986) and TUNG (1986) proposed a polar rising motion in spring to explain the seasonal variation of total ozone. MAHLMAN and FELS (1986) proposed a hypothesis that a substantial reduction of the wintertime planetary-scale eddy activity in the Southern Hemisphere troposphere occurred after 1979, and argued that the expected stratospheric response to the reduced eddy activity in the troposphere accords with the recent ozone decrease and the polar rising motion suggested by TUNG *et al.* (1986) can be generated by the "flywheel effect".

In this paper, a trajectory analysis is made to clarify the transport characteristics in the troposphere and lower stratosphere of the springtime Southern Hemisphere. It is sometimes said that the ozone hole or polar vortex in winter and spring is almost isolated or shielded. The first purpose of this paper is to confirm this feature by the trajectory analysis. The second purpose is to examine whether the springtime rising motion exists in the polar region or not. In addition, a familiar backward trajectory analysis from Syowa Station is made with relation to the cause of the sudden increase of total ozone amount observed at Syowa Station on October 28, 1982 (CHUBACHI, 1984). Preliminary results for a winter case study are presented in YAMAZAKI (1986).

Since a computational accuracy is always a problem in a trajectory analysis, a focus is placed mainly on statistical properties in this paper. Whether the results obtained in this paper are reasonable or not will judge the reliability of the calculation.

2. Data

The dataset used in this study is the 12 hourly global analysis made at the U. S. NMC. Twelve levels are analyzed (50, 70, 100, 150, 200, 250, 300, 400, 500, 700, 850 and 1000 mb). The period is from September 1982 through December 1982. Trajectories are calculated with horizontal winds and vertical velocities derived from the horizontal winds. The stratospheric final warming of the Southern Hemisphere in 1982 was analyzed in detail by YAMAZAKI (1987). Although the stratospheric data above 50 mb were used in YAMAZAKI (1987), they are not used in this study because wind data above 50 mb are not available.

In 1982, intense ozone observations were made and quite low ozone amounts were observed in October of this year at Syowa Station (CHUBACHI, 1984). This is why the year 1982 was selected at the beginning.

3. Method

KIDA (1983a, b) studied the transport characteristics of air parcels in the troposphere and stratosphere with a hemispheric GCM. In the present study, a similar

Table 1. Calculated cases.

Period	Date of missing data
September 10–20	none
September 20–30	00Z September 23
October 10–20	none
October 20–30	00Z October 27
October 30–November 9	12Z November 7
November 20–30	12Z November 24
November 30–December 10	12Z December 2
December 10–20	none
December 20–30	none

analysis is performed but with observed data. Trajectories of air parcels initially placed at a zonal ring are calculated. 72 parcels are placed at 5° longitude increments at certain pressure levels and latitudes. The initial positions of air parcels are at 80°S, 75°S, ··· 80°N and 50 mb, 70 mb, ··· 850 mb. A total number of air parcels calculated in one case is $26136=72\times33\times11$. Air parcels are advected three-dimensionally by the observed winds. Vertical p-velocities are computed by integrating the mass continuity equation assuming vertical p-velocities are zero at 30 mb. 12 hourly observed data are interpolated to 1 hourly data linearly. The time step for the calculation is 1 h and the integration is made for 10 days. All cases we calculated are listed in Table 1 together with dates of missing data.

4. Results

4.1. Diffusivity

There are two transport mechanisms of tracers, advection and diffusion. In this section a diffusion process is investigated.

The same trajectory analysis but during the Southern Hemisphere winter by YAMAZAKI (1986) showed the existence of low-dispersive latitude around 60°S and poleward. This implies the mass exchange is quite weak there during winter and the polar vortex is shielded from the surrounding. In this paper, the trajectory analysis is advanced to the spring season.

Figure 1 shows the latitude-height cross section at day 5 for air parcels which are placed initially at 50, 200 and 500 mb. The initial time is 12Z September 10, 1982. In general, the dispersion takes place along the potential temperature surface (see Fig. 2), because the potential temperature is a conservative quantity with an adiabatic process. Our results are reasonable in this respect. It is noted that the vertical and latitudinal diffusion at 60°S, 50 mb is low. Also within the polar vortex (70–80°S) the latitudinal dispersion is low at 50 mb, though the vertical dispersion is high. During winter, the polar vortex is nearly circular and trajectories from 60°S are also circular (see Fig. 5 of YAMAZAKI, 1986). Figure 3 shows the 10-day trajectories for 4 air parcels initially placed at 50 mb and at 70, 60, 50 and 40°S. All the parcels from 70 and 60°S move around the globe more than one time within 10 days. While, one out of four from 50°S and three out of four from 40°S do not complete one cycle. Since the polar vortex in September is slightly deformed, the trajectories from 60°S are not complete circles. Trajectories from 50 and 40°S are also wavy.

Figure 4 shows the standard deviations in latitudinal direction for 50 mb at days 2, 5 and 10 for the September 10 case together with other cases. Comments on other cases will be given later. In the September 10 case, low standard deviations are found at around 60°S. In the polar region, the standard deviation is smaller than that in middle latitude, but larger than that at 60°S. In the low and middle latitudes, the standard deviations are large and increase monotonically with time, while they do not increase monotonically in the polar regions.

The time variation of the standard deviation for the September 10 case is shown in Fig. 5 together with other cases. The standard deviation at 60–80°S increases rapidly within the first day and stays at around 4–8 degrees afterward. The initial

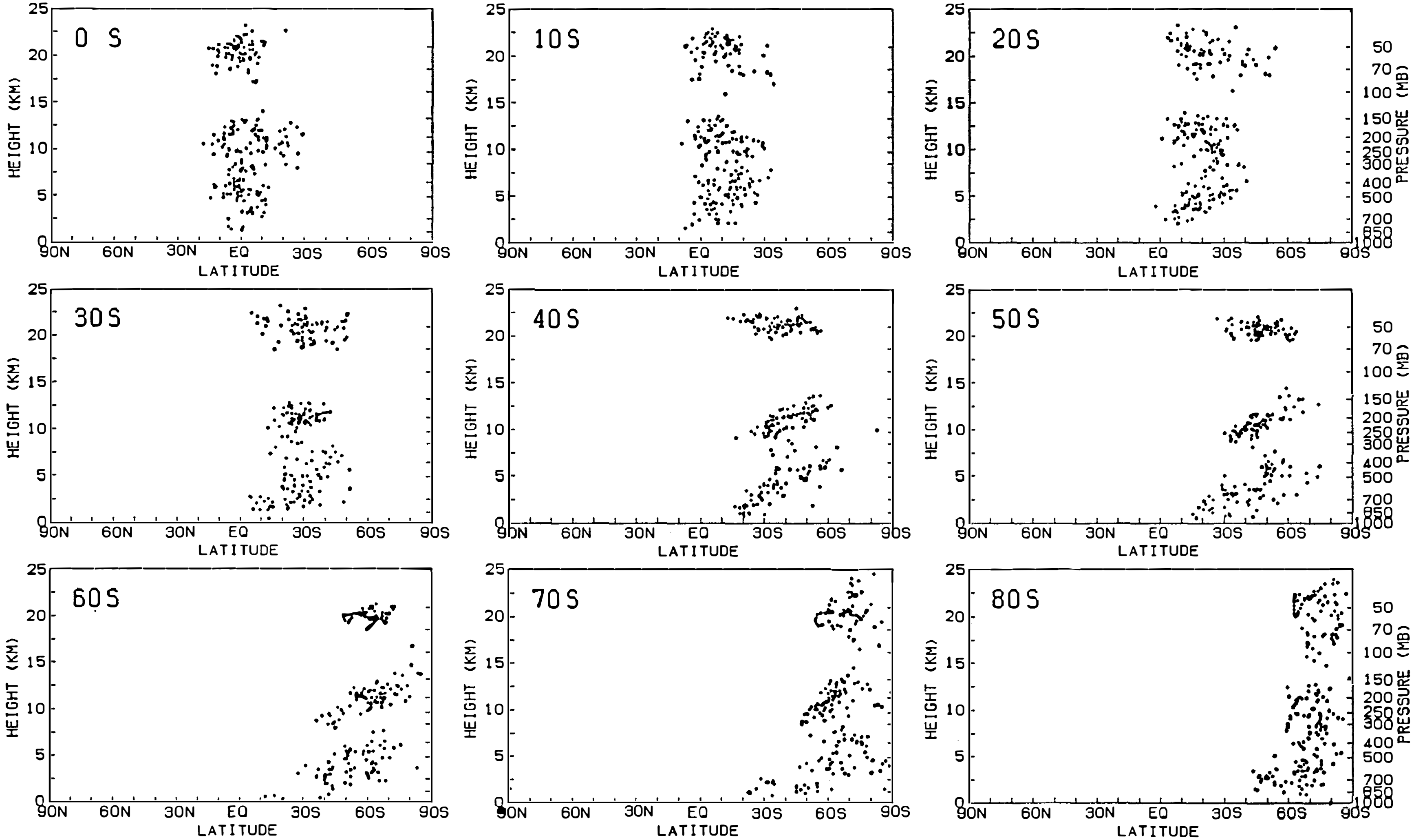

Fig. 1. Latitude-height distributions of air parcels at day 5. The initial time is 12Z September 10, 1982. The initial positions are at 50, 200 and 500 mb. The latitudes are from 0 to 80°S (from top left to bottom right).

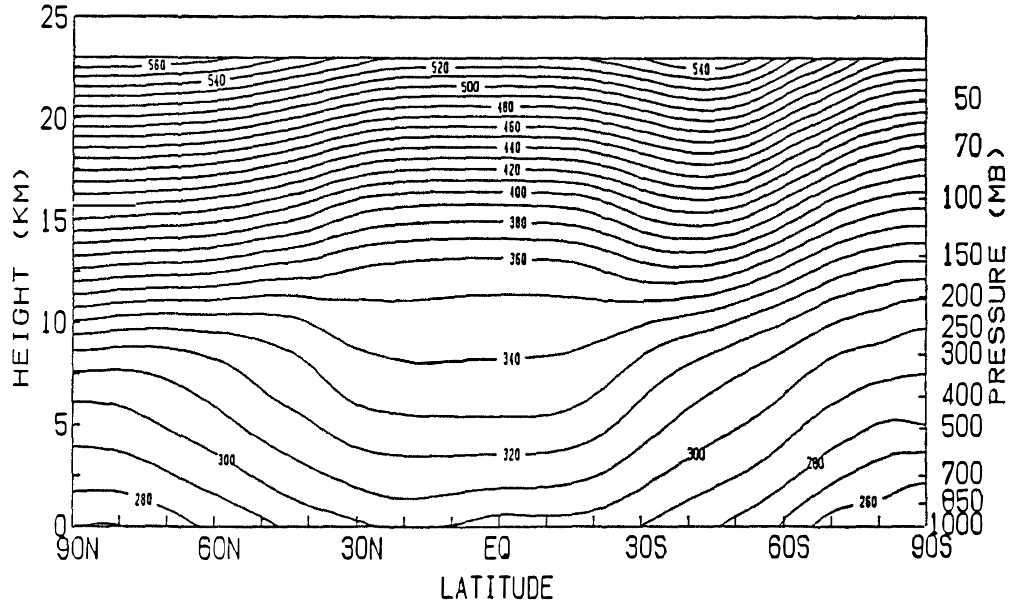

Fig. 2. Zonal and 10-day mean potential temperature during the period from 12Z 10 September 1982 through 12Z 20 September 1982. Contour interval is 10 K.

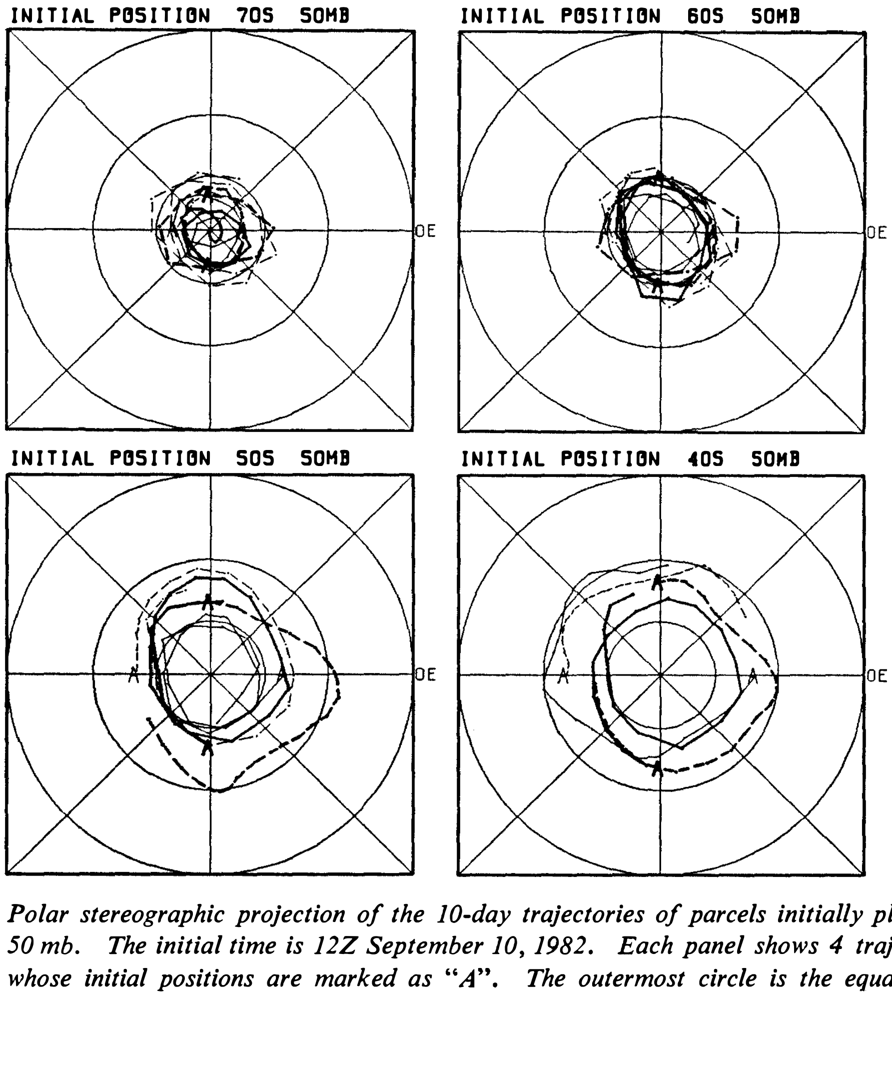

Fig. 3. Polar stereographic projection of the 10-day trajectories of parcels initially placed at 50 mb. The initial time is 12Z September 10, 1982. Each panel shows 4 trajectories whose initial positions are marked as "A". The outermost circle is the equator.

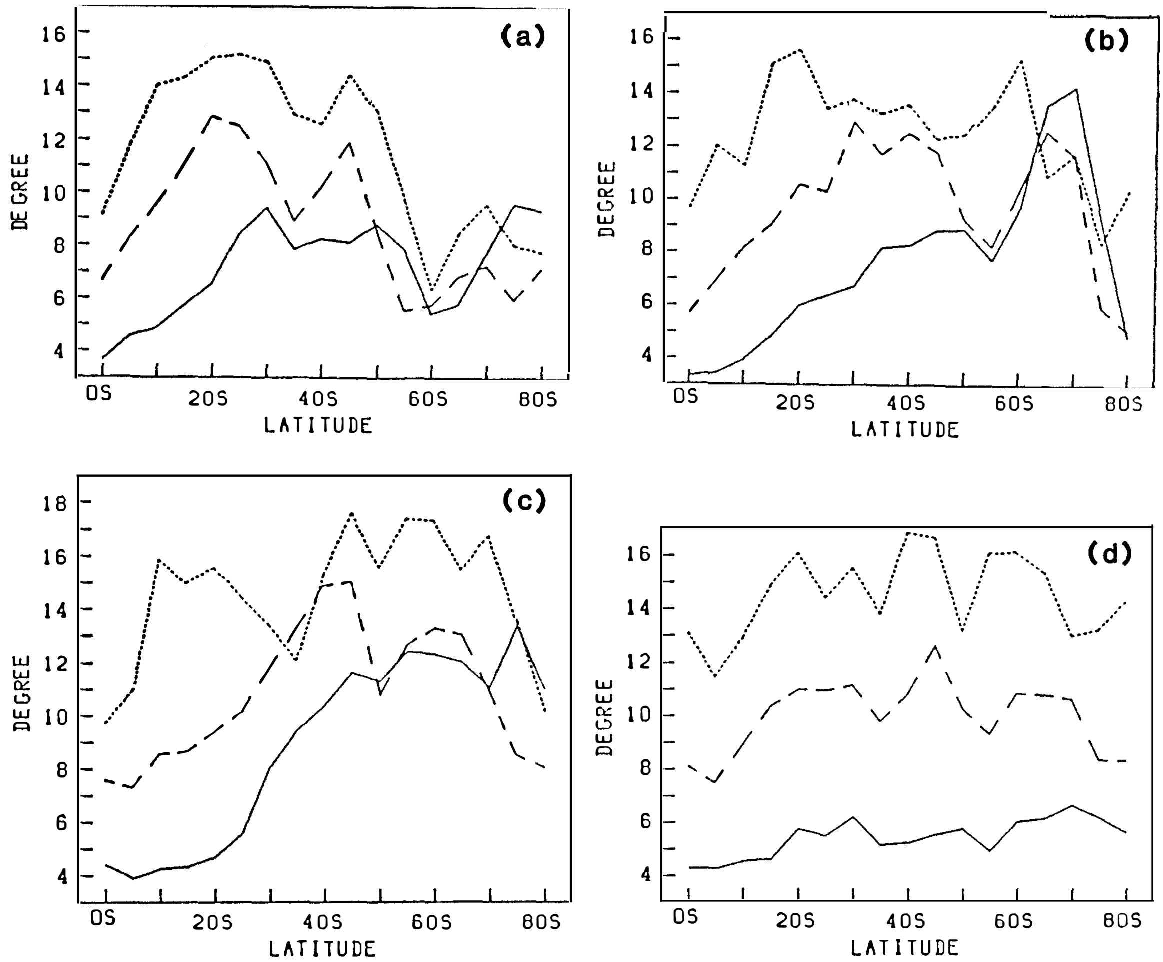

Fig. 4. Standard deviations of the latitudinal displacements of air parcels at 50 mb on day 2 (solid line), day 5 (dashed line) and day 10 (dotted line). The initial times are, a: 12Z September 10, 1982, b: 12Z October 20, 1982, c: 12Z November 20, 1982, d: 12Z December 20, 1982.

growth is caused by the deformed or shifted polar vortex. No growth after day 1 suggests that the actual latitudinal dispersion across the boundary of the polar vortex is small and parcels are almost trapped within the polar vortex. At 0–40°S, the initial growth of the standard deviation is not so large but the standard deviation increases nearly monotonically during the period. At 50°S, the variation of the standard deviation shows the intermediate feature.

To check the argument mentioned above, an experimental trajectory analysis was made with a fixed flow field. The initial time is 12Z September 10 the same as before and the trajectories are computed for 10 days with the initial flow field. In this artificial case, each air parcel will come back to exactly the same position with certain periodicity. In fact, the calculation showed the above feature. It thus proves that our method of calculation is sufficiently accurate. Figure 6 shows the time variation of standard deviation at 50 mb for this experimental case. At 40–80°S, the standard deviation stays at about 5–7 degrees level after the rapid initial growth. At 60–80°S, the standard deviation in this case has similar magnitude to that in the standard September 10 case. In particular, the standard deviation at 60°S in this case is

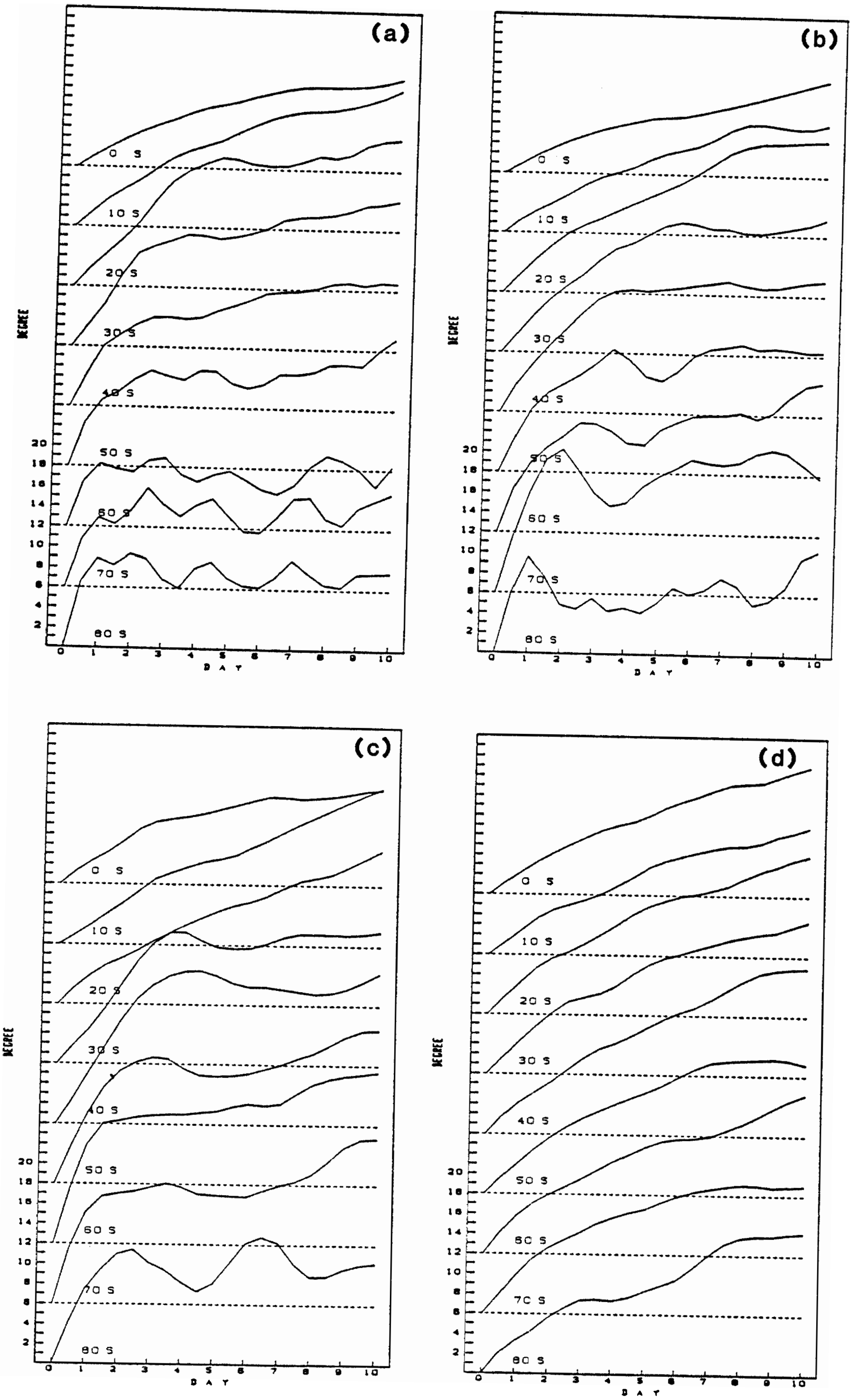

Fig. 5. Time variations of the standard deviation of the latitudinal displacements at 50 mb, 0–80°S. At the initial time, the values are zero. The initial times are the same as in Fig. 4 (from left to right).

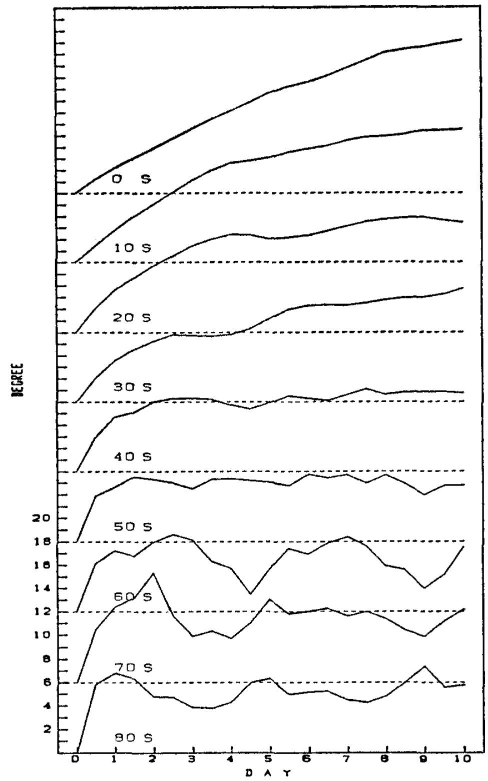

Fig. 6. Same as in Fig. 5 except for the September 10 experimental case.

almost the same as that in the standard case. This means the latitudinal dispersion is caused mainly by the deformed or shifted polar vortex.

The latitudinal dispersion at 60°S in the September 10 case (Figs. 4 and 5) is small compared with other latitudes and other cases. This low dispertive latitude around 60°S probably acts as a barrier against ozone transport across this latitudinal region during early spring. Although the large latitudinal gradient of ozone is formed at around 60°S during early spring in the Southern Hemisphere (see, for example, STOLARSKI *et al.*, 1986; SCHOEBERL *et al.*, 1986), the above analysis suggests the horizontal eddy transport of ozone is small at 60°S.

The September 20 case is similar to the September 10 case. In the October 20 case (Figs. 4 and 5), the standard deviation in the polar region is very large. During this period large planetary wave activity was observed in the stratosphere which led a final warming in the upper stratosphere (YAMAZAKI, 1987). The ozone in the polar region increased and that in mid-latitudes decreases during this period due to planetary wave activity (see Fig. 2 of BOWMAN, 1986). The large initial growth of the standard deviation (Fig. 5) reflects this planetary wave activity.

The November 20 case is somewhat similar to the October 20 case. The standard deviation at 80°S is larger than that in the October 20 case. During this period (November 20–30), the amplitude of planetary wave was not so large as the October 20 case, but the polar vortex in the lower stratosphere finally broke down. This breakdown of the polar vortex caused large standard deviations in the polar region. In both November 20 and October 20 cases, the time variation of the standard deviation in the polar region is not monotonic.

In the December 20 case after the summer circulation has established, the feature of the standard deviation completely differs from the other cases. The standard deviation shows similar magnitude in the whole Southern Hemisphere and the time variation is monotonic everywhere.

From the above results, we can distinguish three stages of diffusivity during the winter-to-summer period. During stage 1 (from mid-winter to September), the polar vortex is shielded from the surrounding and diffusivity at 60°S and poleward is quite low. During stage 2 (October and November), the polar vortex is largely deformed and it is being encroached by planetary wave activities. And the diffusivity in the polar region is large. However, note that not all large planetary waves contribute to the horizontal mixing but the irreversibility is important for net transport of ozone (BOWMAN, 1986). In this respect, the final breakdown is one of the most important phenomena for tracer transport. Stage 3 (December and afterward) is the stage where the summer circulation prevails and diffusivity shows a homogeneous and turbulent character.

SAM II measurements of aerosols showed a rapid and intense increase of extinction ratio in the Antarctic region in November 1982 (MCCORMICK and TREPTE, 1986). It is the time when volcanic material originating from the eruption of El Chichon in March and April 1982 entered the southern polar region and when the final breakdown of the polar vortex occurred. This behavior of volcanic aerosols can be well explained by the transport characteristics studied here.

4.2. Meridional circulation in the polar region

In this section the advective process which is the mean movement of air parcels is investigated. If we trace the center of gravity in a meridional plane, the meridional circulation in the Lagrangian sense would be obtained. This motion is the "generalized Lagrangian-mean" (GLM) motion formulated and discussed by ANDREWS and MCINTYRE (1978) and MCINTYRE (1980). Although their original GLM theory is based on the assumption that the initial disturbance is absent, this assumption is not needed and the GLM theory can be applicable to the case when the finite amplitude disturbance exists initially (NODA, 1987).

A spatially inhomogeneous diffusion could apparently cause movement of the center of gravity even in the absence of truly advective process as discussed by KIDA (1983a). To reduce the artificial effect due to the inhomogeneous diffusion, forward and backward calculations are performed following KIDA's idea. The forward calculation is the same as that in the previous section. The backward calculation is to trace back air parcels initially placed on the latitudinal ring to the past. We call this the backward GLM motion. The advection of air parcels free from the apparent motion due to inhomogeneous diffusion can be obtained by averaging the two of the forward and backward GLM motions.

The top panel of Fig. 7 shows the forward GLM motion for 10 days starting from 12Z September 10, 1982. The middle one shows the backward GLM motion for 10 days from 12Z September 20, 1982. The bottom one shows the sum of these two motions. In the forward calculation, a large equatorward motion is seen in the

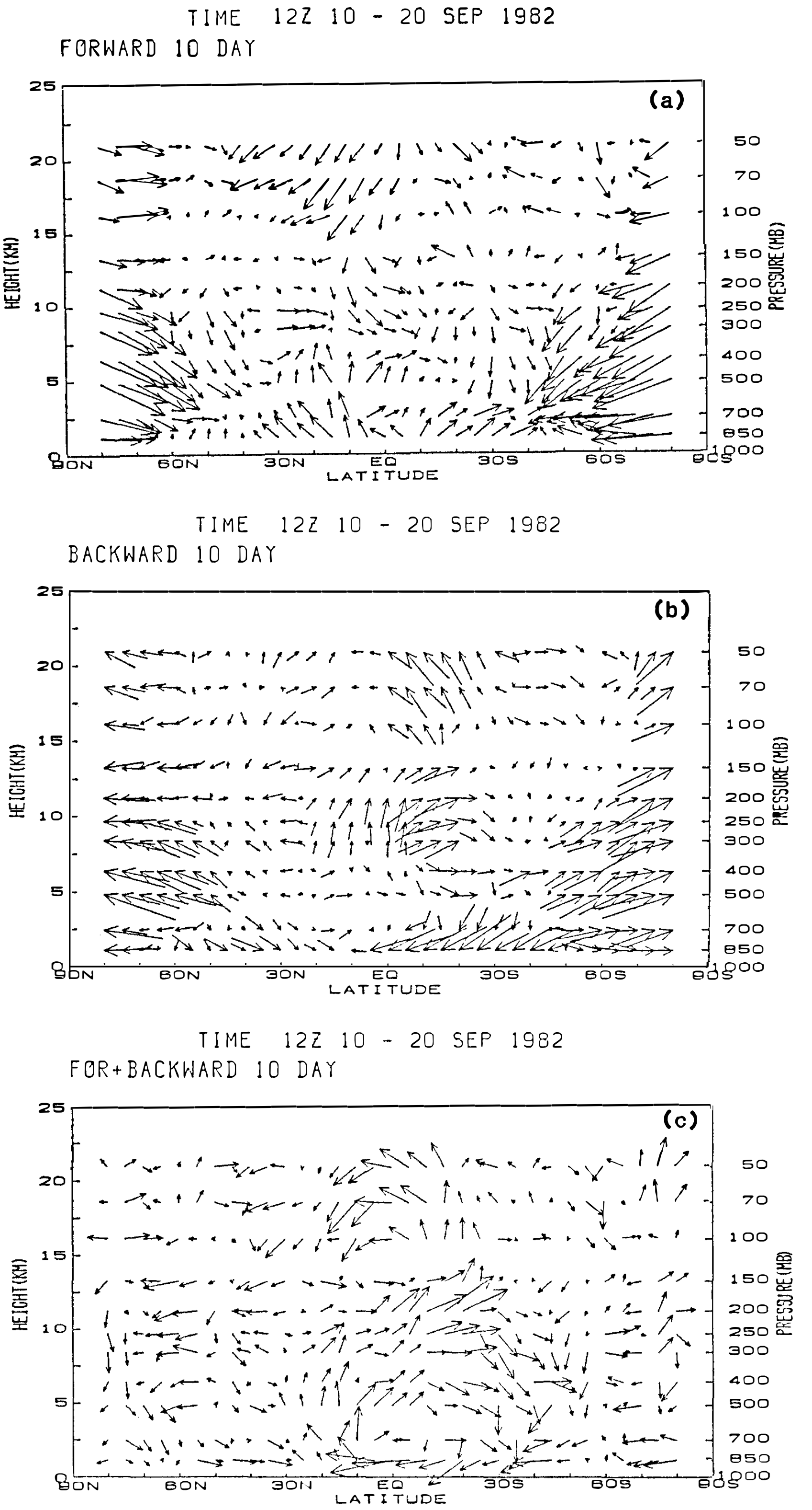

Fig. 7. Generalized Lagrangian Mean (GLM) motion for 10 days starting from 12Z September 10, 1982 (a). Backward GLM motion for 10 days starting from 12Z September 20, 1982 (b). The sum of the above two motion (c).

high-latitude troposphere and a large convergence is found in mid-latitudes. This tropospheric feature is similar to the Lagrangian-mean motion associated with a growing Eady wave (URYU, 1980). It is inferred that baroclinic waves contribute mostly to the tracer transport in the troposphere of the extratropics. In the backward calculation, on the other hand, a large poleward motion in high-latitudes and a divergence in mid-latitudes are seen. However, net advective motion (the sum of the above two) is small.

In the tropics, the net advective motion shows the Hadley circulation. In this season, the Southern Hemisphere Hadley cells is still stronger than that in the Northern Hemisphere. In a sense, the Hadley cell is a real substance, *i.e.*, it can be seen in both the Eulerian mean and the Lagrangian mean circulations. On the other hand, the Ferrel cell cannot be seen in the Lagrangian mean circulation.

It is noted that net upward motion is found in the region from 65 to 80°S at 50–100 mb level and net downward motion is found in the region from 50–60°S at 50–100 mb level. This cell in the meridional plane accords with that proposed by TUNG *et al.* (1986) and TUNG (1986). Its vertical scale is small so that the polar upward motion does not seem to be able to trace back to the lower tropospheric level. The maximum value of upward motion is about 92 m day^{-1} which is close to the value suggested by TUNG *et al.* (1986). Our calculation seems to support the existence of the springtime upward motion over the polar vortex region and downward motion over the ozone maximum region.

A similar cell is calculated in the September 20 case and the maximum value of upward motion is about 66 m day^{-1}. However, such a systematic motion is not calculated in other cases. Therefore, the cell seems to appear only during September and possibly in August. This accords with the fact that a large seasonal depletion of the polar ozone takes place during September and the minimum of the monthly mean polar ozone is seen in October.

4.3. Sudden increase of ozone at Syowa Station

At Syowa Station (69°00′S, 39°35′E) a sudden increase of ozone was observed on October 28, 1982 (CHUBACHI, 1984). Hereafter this event is called the ozone event. At the same time, a rapid temperature rise was observed at the level between 20 and 400 mb. Comparing the vertical profiles of ozone on October 27 and 28, CHUBACHI (1984) suggested the downward shifting of about 2 km can account for the sudden increase of ozone. The temperature change is consistent with this hypothesis.

Backward trajectory calculations from the horizontal position of Syowa Station are performed in this section to confirm the above hypothesis. The heights of air parcels which arrived at 100 mb above Syowa Station are shown in Fig. 8. Parcels arrived at Syowa Station at 12Z, October 28 and 29 experienced strong downward motions during 12 h just before the arrivals. These parcels were at around 90 mb on October 20. On the other hand, the parcels which arrived at Syowa Station at 12Z October 27 (before the ozone event) and 12Z, October 30 (after the ozone event) did not show any strong downward motion and they were at around 120–140 mb on October 20. The parcel which arrived at 12Z October 26 shows the moderate downward motion just before the arrival at Syowa Station but it was at about 115 mb

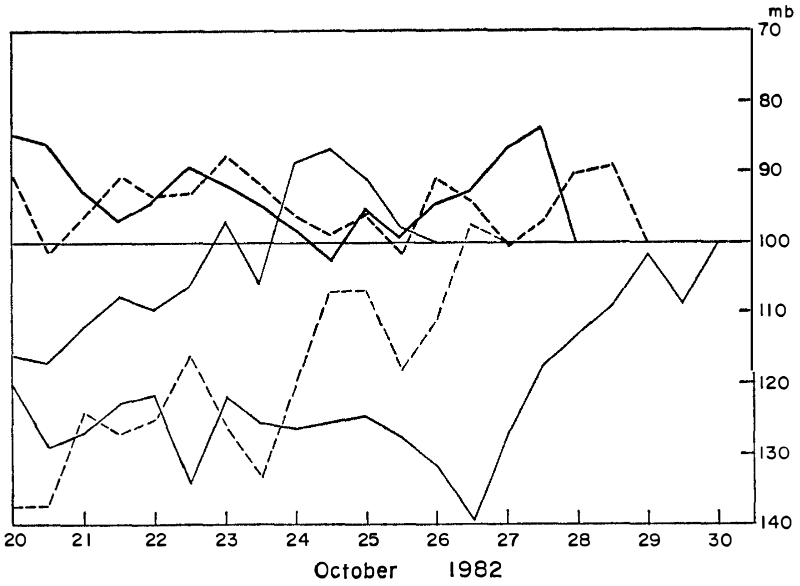

Fig. 8. Heights of air parcels which arrived at 100 mb above Syowa Station at 12Z October 26 (thin solid line), 27 (thin dashed line), 28 (thick solid line), 29 (thick dashed line) and 30 (thin solid line) of 1982.

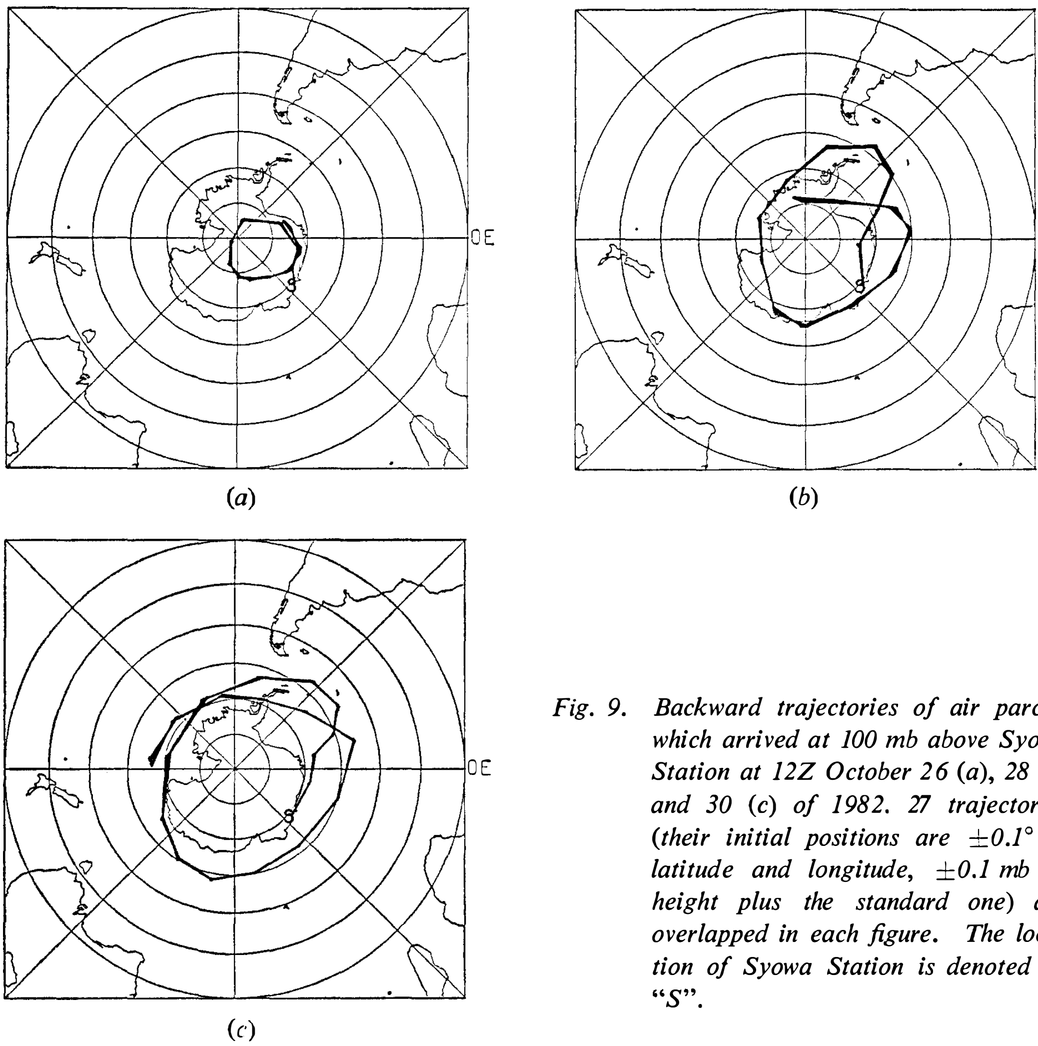

Fig. 9. Backward trajectories of air parcels which arrived at 100 mb above Syowa Station at 12Z October 26 (a), 28 (b) and 30 (c) of 1982. 27 trajectories (their initial positions are ±0.1° in latitude and longitude, ±0.1 mb in height plus the standard one) are overlapped in each figure. The location of Syowa Station is denoted by "S".

on October 20. Since ozone amount increases with height in this altitude range, the air parcels which arrived at Syowa Station during the ozone event are originated from the ozone-rich upper levels. The reverse is true for those before and after the ozone event.

After the ozone event, ozone amount decreased slowly but never returned to low values observed before the event (CHUBACHI, 1984), although the parcel originated from the ozone-poor lower levels. This puzzle can be solved by the inspection of horizontal trajectories (Fig. 9). On the average, the polar vortex was shifted into the direction of the Greenwich meridian and the ozone maximum was seen near the dateline at 60°S during October (STOLARSKI *et al.*, 1986). With this in mind, it is easily understood that air parcels came to Syowa Station from the ozone-poor polar vortex region before the ozone event (October 26). After the ozone event (October 30), air parcels from the ozone-rich lower latitude region arrived at Syowa Station. Therefore, the decrease of ozone after the ozone event was not so large.

In summary, the present trajectory analysis is consistent with the observation at Syowa Station. A downward motion is mainly responsible for the sudden increase of ozone at Syowa Station on October 28, 1982, although the horizontal advection is also important.

5. Discussion and Summary

Vertical velocity is a variable hard to estimate accurately from observations. The assumption of $\omega=0$ at 30 mb may be a little crude for estimating vertical velocity. We also calculated with the condition of zero vertical p-velocities at 0 mb for one case. However, the results were almost the same and there seems to be no need to change the conclusions mentioned above. The usage of independent data such as the ECMWF analysis may help further justifying the results obtained here. Further studies are needed to obtain more solid conclusions. Nevertheless, several facts, such as that the dispersion took place along the potential temperature surface and that the backward trajectory analysis from Syowa Station did not contradict the observation by CHUBACHI (1984), suggest the present analyses are at least qualitatively justifiable.

The main results obtained in this paper and YAMAZAKI (1986) are summarized as follows.

(1) The diffusivity at 60°S and poleward in the lower stratosphere is low during winter and early spring. The diffusion in December is homogeneous and turbulent in the lower stratosphere.

(2) The meridional motion similar to that suggested by TUNG *et al.* (1986) is obtained in September.

(3) The sudden increase of ozone at Syowa Station on October 28, 1982 was primarily caused by a strong downward motion.

In the present paper, the transport characteristics in the Southern Hemisphere are studied for September–December of 1982. It will be interesting to investigate other years in relation to the recent springtime ozone depletion over Antarctica. Also a similar analysis for the Northern Hemisphere will help clarifying the transport characteristics peculiar to the Southern Hemisphere. Although the back-and-forth motion is expected to be close to the "diabatic circulation", its physical base is not obvious. Further theoretical and observational studies are needed.

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