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STUDIES OF MIDDLE ATMOSPHERE DYNAMICS UNDER THE POLAR PATROL BALLOON (PPB) PROJECT: PRESENT STATUS AND FUTURE PLANS

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Abstract: Studies of middle atmospheric dynamics under the PPB project have two aspects. On one hand, they are necessary to predict a feasibility of PPB flight. Recent studies on global-scale disturbances (planetary waves) over the Antarctic stratosphere suggest that the mid-summer (December–January) flight at 30–40 km altitudes has a trajectory with meridional fluctuations with ±2° around the initial latitude. The mid-winter (June–August) flight in the Antarctic stratosphere may be much circumpolar than that in the Arctic. The spring (October–November) and autumn (February) flights are not adequate for circumpolar observations. We predict that the north-south drift due to small-scale disturbances (gravity waves) may be within ±0.3°, although this must be confirmed in the future. On the other hand, trajectory analysis and balloon-borne anemometry of PPB would give us useful information for studying the transport process and the gravity-wave effect in the Antarctic stratosphere.

1. Introduction

"Polar Patrol Balloon (PPB)" project by the National Institute of Polar Research (NIPR) started in 1984 to establish a station network in the stratosphere over the Antarctic region for geo-astrophysical observations (NISHIMURA *et al.*, 1984a, b, 1985; KODAMA and FUKUNISHI, 1984; NAGATA *et al.*, 1985). The PPB Working Group (PPBWG) has been improving the ballooning technology and predicting the balloon trajectory. Technologically, the altitude control by auto-ballasting and the satellite-linking data acquisition using the ARGOS system has been well done for July 1985 flights from Norway to Iceland (OHTA *et al.*, 1986) and for an October 1986 flight of about 5900 km eastward from the Sanriku Balloon Center (SBC) of the Institute of Space and Astronautical Science (ISAS).

The meteorological studies by PPBWG have shown that PPB is feasible in the mid-summer season (*e.g.*, NISHIMURA *et al.*, 1985). In this case the circumpolar period was about 22 days westward, and the north-south deviation was ±2° at around 30 km altitude. These conclusions are mainly based on well-established knowledges on the northern hemispheric stratosphere (see HOLTON, 1975, for a review). The summer easterly is much steadier than the winter westerly disturbed by global-scale waves propagating from below. In fact the Norway–Iceland flights clearly showed the steadiness of summer easterlies. PPBWG has decided to make the first launch of

PPB at Syowa Station in December 1987 by the 28th Japanese Antarctic Research Expedition (JARE-28).

Our knowledges of the stratosphere have been greatly increased by the Middle Atmosphere Program (MAP) carried out in 1982–1985. Mean wind distributions in the southern hemisphere are now available using rocketsondes (KOSHELKOV, 1984, 1985) and satellites (BARNETT and CORNEY, 1985a, b). The most sensational fact found out in the Antarctic MAP is the so-called "ozone hole", that is, the total ozone amount becomes very small every October since late 1970's (CHUBACHI, 1984; FARMAN *et al.*, 1985). YAMAZAKI (1986, 1987) has calculated stratospheric air trajectories in the southern hemisphere using the 12-hourly global grid-point data set analyzed by the National Meteorological Center (NMC) of US. He showed that the circumpolar flows to the south of 60°S are not disturbed by global-scale waves even in winter. In Section 2, we shall re-examine our PPB trajectory predictions with those recent results of the middle-atmosphere dynamics.

The researches mentioned above can predict the dispersion of PPB trajectory only due to the mean flow and large-scale waves. However, there are small-scale waves throughout the earth's atmosphere, which will affect the air transport directly by the turbulent breakdown and also indirectly through the meanflow acceleration (or deceleration). KANZAWA *et al.* (1986) have observed such a kind of wave for the first time in the Antarctic stratosphere by short-time interval rocketsonde observations. As mentioned in Section 2, we cannot exactly predict the contribution from the small-scale waves, because the observational data are still not enough. On the contrary, this suggests that PPB would be highly valuable for researches of those waves, which will be discussed in Section 3.

2. Prediction of PPB Trajectory

Stratospheric wind variations can be classified into four categories (see Fig. 1): 1) monthly-mean zonal-mean zonal wind, 2) monthly-mean zonal-mean meridional wind, 3) large-scale disturbances which have global spatial scales and periods longer

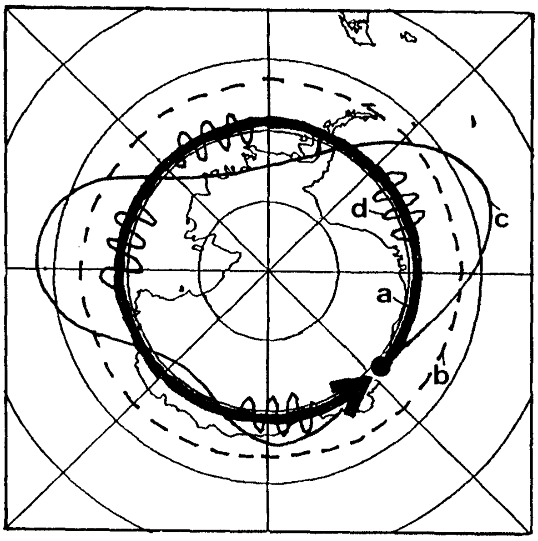

Fig. 1. Schematic illustration of PPB trajectory drift due to four categories of the stratospheric wind variations: a) the mean zonal flow; b) the mean meridional flow; c) the planetary waves; and d) the internal gravity waves.

than 1 day, and 4) small-scale disturbances which appear sporadically and locally.

2.1. *Mean zonal wind and PPB circumpolar period*

We predict the mean circumpolar period of PPB for various months, altitudes and latitudes (Table 1), which can be given by the circumference L of 70°N circle ($\simeq$13750 km) divided by the monthly-mean zonal-mean zonal wind U (KOSHELKOV, 1985). The flight period decreases monotonically with altitude, since the zonal wind speed increases with altitude. As shown in previous reports, the winter westerly is much stronger than the summer easterly, and the flight period in winter is much shorter than that in summer.

Table 1. Mean flight time (days) for the 70°S circumference ($\simeq$13750 km), calculated based on KOSHELKOV *(1985).*

Altitude	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
40 km	3	2	2	4	−53	−10	−12	−159	7	3	3	3
35	3	2	2	4	∞	−12	−18	∞	8	4	3	3
30	3	2	2	3	32	−20	−27	159	10	5	4	3
25	4	3	3	4	16	−53	−53	53	13	6	4	4
20	5	4	4	6	12	∞	−159	40	8	9	7	5

Table 2. Mean flight time (days) considering a northward drift due to global-scale disturbances calculated in Table 3.

Altitude	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
40 km	3	2	3	7	−27	−11	−12	−20	8	4	3	3
35	3	2	3	6	∞	−14	−17	∞	10	4	3	3
30	3	3	3	5	−63	−23	−25	−40	13	6	4	3
25	4	3	3	5	48	−44	−53	113	16	7	5	4
20	5	5	5	6	17	∞	167	36	18	11	7	6

If the mean wind is constant, the flight period becomes longer (shorter) for the lower (higher) latitude, because $L \propto \cos\varphi$ (φ: latitude). However, the meridional distribution of mean zonal winds are nearly that of a solid rotation ($U \dot{\propto} \cos\varphi$). Hence, the circumpolar period L/U does not depend on the latitude, and becomes almost constant for a given month and altitude (see Fig. 2). In order to confirm this, we recalculated the circumpolar periods (Table 2) using L and U of the most northern drift predicted in Subsection 2.3.

Based on the mean zonal-wind data, we can also estimate the directly-tracking period of PPB from a receiving station over the Antarctica. The period (h) is given by $4.12\,(\sqrt{H_B}+\sqrt{H_S})/U$ (km/h), where H_B and H_S are altitudes (m) of balloon and station, respectively. Clearly it becomes longer in higher latitudes, since $U \dot{\propto} \cos\varphi$ (see again Fig. 2). Taking a wind-speed variation of ±3 m/s (*cf.* Subsection 2.4) into account, we expect that a 30 km-January PPB can be tracked for 16–48 h from Syowa Station (69°S) and for 32–96 h from McMurdo Station of US (78°S). A recent Antarctic ballooning by US (BERING *et al.*, 1987) seems to support our estimations. Therefore, if we wish to perform *only* a long-duration flight (without requesting an exact circumpolar flight), we had better choose such a ballooning near the South Pole

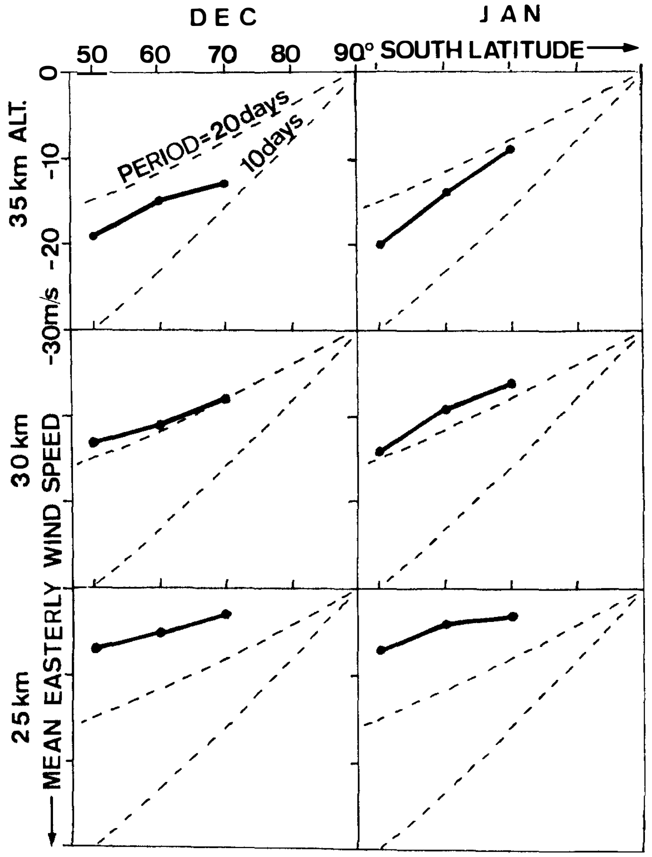

Fig. 2. Meridional distributions of the mean zonal winds, based on KOSHELKOV *(1985).*

rather than PPB launched at Syowa Station.

2.2. Mean meridional flow and PPB drift

At the flight altitudes of PPB, the meridional wind is very weak ($\lesssim 1$ m/s) in monthly zonal mean, and it is mainly due to some wave disturbances which have periods and wavelengths shorter than one month and latitudinal circle, respectively. If a balloon flight is performed in the lower stratosphere (lower than 20 km altitude) over the mid-latitudes, the balloon may be drifted considerably by a poleward mean flow. In case of a flight in the lower-latitude mesosphere (higher than 50 km altitude), the balloon may be drifted by a mean meridional flow toward the winter pole. Since the flight of PPB is performed in the higher-latitude middle stratosphere, we need not consider the north-south drift due to the mean meridional flow.

2.3. Global-scale waves and PPB drift

The global-scale disturbances, or "planetary waves", can be classified into two groups: forced stationary waves and free traveling waves. The predominant disturbances in winter mentioned in Section 1 are included in the former group.

The activity of the stationary planetary waves has been quantitatively studied by spectral analyses of the monthly-mean satellite observations for the first and second longest zonal-wavelength modes (BARNETT and CORNEY, 1985b). We can estimate the extent of north-south displacement of PPB due to these disturbances as $g\cdot\Delta\Phi/fU$,

Table 3. Maximum north-south deviations (±degrees in latitude) due to the global-scale waves for a circumpolar flight at 70°S, calculated based on B*ARNETT and* C*ORNEY (1985b).*

Altitude	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
40 km	2	3	5	9	12	3	1	17	2	1	3	2
35	2	3	5	8	∞	4	1	∞	3	2	3	3
30	2	3	4	7	23	7	2	24	4	3	4	3
25	3	3	4	8	11	21	7	9	5	4	4	3
20	4	5	6	10	8	∞	26	8	7	6	4	4

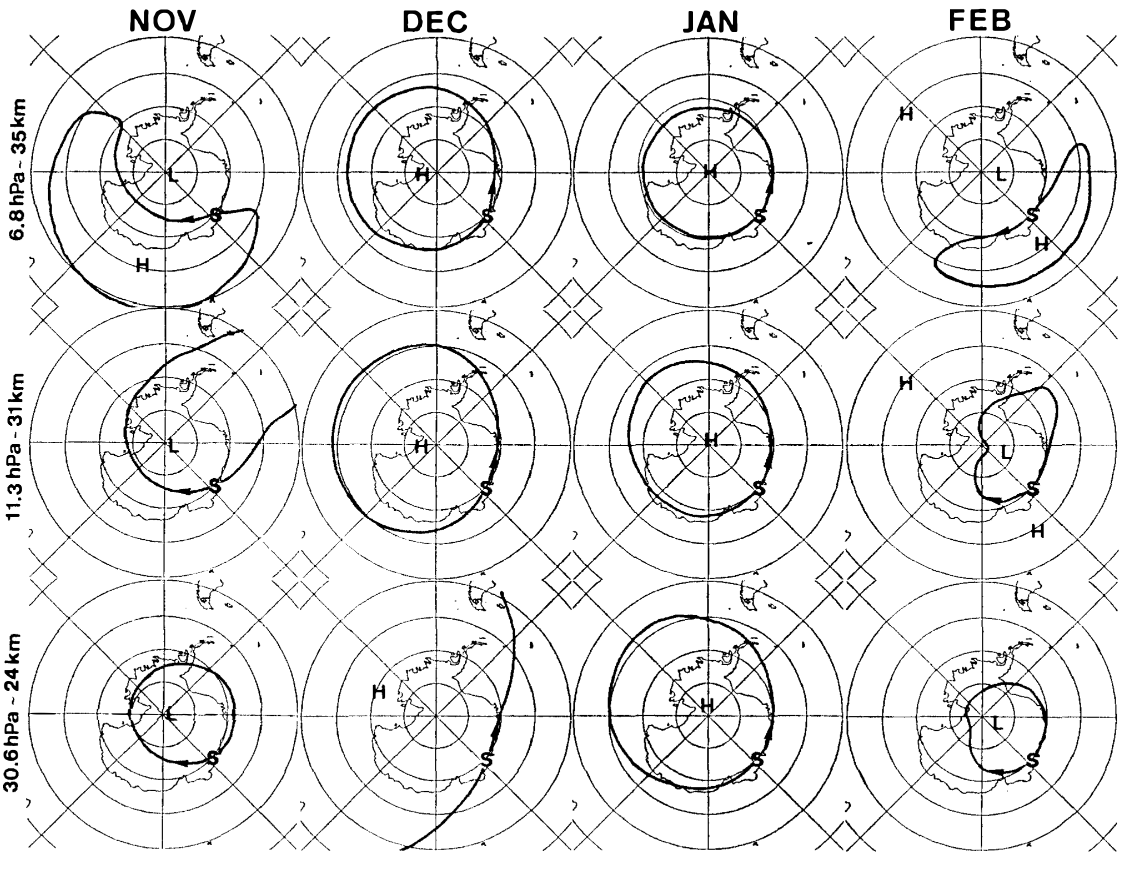

Fig. 3. Monthly-mean streamlines, calculated based on B*ARNETT and* C*ORNEY (1985a, b).*

where g, f and $\Delta\Phi$ are the gravity acceleration, the Coriolis parameter ($2\pi \sin \varphi / 86164$ s) and the perturbed geopotential height (Table 3). We show the mean streamline passing the location of Syowa Station in Fig. 3.

According to these results we state that the mid-summer season from late December through January is most appropriate for PPB flights. As long as the stationary planetary waves are concerned, the north-south drift of PPB launched in early January to an altitude higher than 30 km would be within ±1°. However, we must note that the most appropriate season is very short in the Antarctica. The reversal of the zonal wind direction occurs in November as well as February, and then PPB cannot take a circumpolar trajectory. It is noteworthy that southern hemispheric winter flights do not drift so much as expected in the previous reports based on the northern-hemispheric data analyses. The stationary planetary waves near the Antarctic are less active than those near the Arctic, which may explain why the ozone hole appears solely in the Antarctic (*cf.* YAMAZAKI, 1986, 1987).

On the other hand, traveling planetary waves have typical periods (relative to the earth) of ~5, ~10 and ~16 days. Although they are now under investigation, some of them seem to have innegligible amplitude even in summer. Since they have periods somewhat shorter than the mean flight time of PPB in summer, their contribution might be almost canceled after a circumpolar flight. As an approximation, the amplitude of those waves may be equal to or less than that of stationary waves.

The net effect of both the stationary and traveling waves can be estimated using the data obtained by a routine meteorological observation network. YAMAZAKI (1986, 1987) has developed a computation program to calculate three-dimensional air trajectories using a grid-point wind data set. Figure 4 shows 10-day trajectories

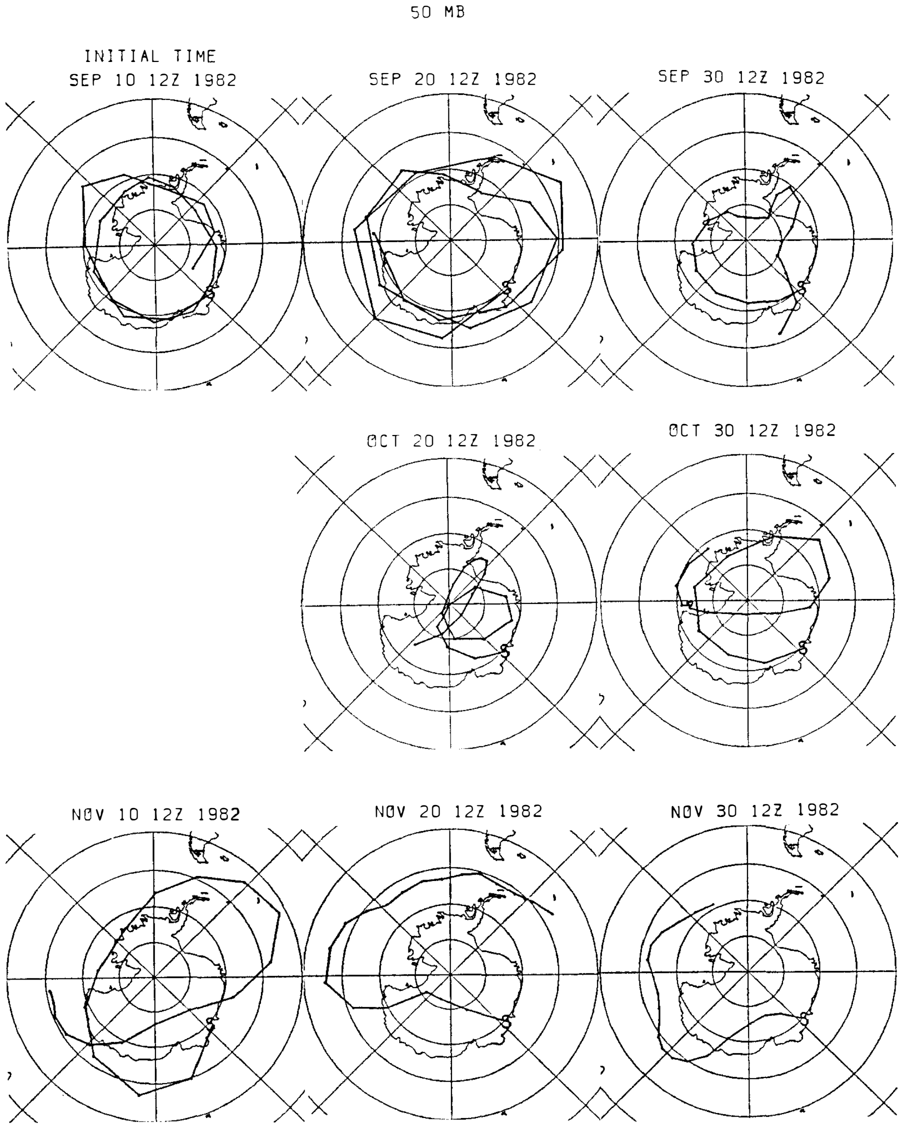

Fig. 4. 10 day trajectories of air parcels initially placed at 50 hPa altitude over Syowa Station (69.0°S, 39.6°E), calculated using grid-point data set analyzed by NMC. The initial times are denoted in each panels. For details of calculations, see YAMAZAKI*(1986, 1987).*

of air parcels located initially at 50 hPa (~21 km) altitude over Syowa Station in September–November. We can see that the planetary-wave activity in the Antarctic lower stratosphere is not so strong during the late winter to spring. Therefore, PPB is considered to fly near the Antarctic even in winter.

Because of the data limitation, the results for higher altitudes in summer have not been calculated, but we are expecting that the PPB's trajectories will be approximately along a latitude circle in mid-summer middle-higher stratosphere because of weakness of the planetary waves. However, it should be noted that the trajectory will be affected locally by small-scale variations which do not appear in the grid-point data set based on the routine meteorological network including satellite observations.

2.4. *Small-scale disturbances and PPB dispersion*

The small-scale disturbances mentioned above is so-called "internal gravity waves", which exist probably in the whole atmosphere. We can detect their activity as standard deviation of the routine meteorological observations in time and/or altitude, but more direct and quantitative information has been obtained during the MAP period. Typical values of the wind-velocity amplitude, horizontal wavelength, vertical wavelength and period (relative to the ground) are ±5 m/s, the order of 100 km, the order of 1 km and several hours to 1 day, respectively (see YAMANAKA, 1985, 1987a, b).

In a statistical sense, the standard deviation of 5 m/s corresponds to the magnitude of diffusion of $(\pm 5\ \mathrm{m/s})\cdot T/2\pi$ approximately, where T is an effective period of such wave disturbances. Theoretical range of T in a rest atmosphere at 70° latitude is between 5 min to 13 h. The recent rocketsonde observations in the Antarctica by KANZAWA *et al.* (1986) have found $T \simeq 10$ h. Based on them, we can state that the magnitude of diffusion is about ±30 km, or ±0.3° in latitude.

Therefore, the contribution of the small-scale disturbance to the north-south drift is much smaller than that from the large-scale disturbances described in the previous subsection. Since the wavelengths and periods of the internal gravity waves are quite smaller than the circumpolar flight span and time of PPB, their net contribution to the north-south deviation of PPB after a circumpolar flight must be canceled.

3. Middle Atmosphere Dynamics Using PPB

PPB allows us to make two types of future studies on the middle atmosphere dynamics. One is a passive utilization of PPB, that is, to analyze the trajectories of PPB for any objectives. The other is an active utilization of PPB, that is, *in-situ* observations of wind variations by balloon-borne instruments.

3.1. *PPB trajectory analysis*

As mentioned in Section 2, our predictions of the PPB trajectory are still not so accurate. This implies that the PPB trajectory provides valuable information on the middle-atmosphere dynamics. Concerning the planetary-wave studies, the location measurements by ARGOS system at roughly one hour intervals are enough to obtain a Lagrangian wind field (relative to an air parcel). If several PPBs are launched, an Eulerian wind field (relative to the earth) may be obtained. Similar studies have been carried out near the tropopause over somewhat lower latitudes (see Table 2 of NAGATA *et al.*, 1985, for a summary of the previous studies on the atmospheric dynamics using constant-level balloons).

Comparing observed PPB trajectories with those predicted from analyses based on the routine observations using rocketsondes or satellites, we could estimate how the gravity waves contribute to the air transport processes. If we obtain the location of PPB every one minute or so by direct ranging from several Antarctic bases, we can also analyze the internal gravity waves (see YAMANAKA, 1985, 1987a, b, c).

3.2. Balloon-borne anemometry

Breaking of the internal gravity waves plays an important role in the momentum budget throughout the earth's atmosphere (TANAKA and YAMANAKA, 1985). No techniques could detect the wavebreaking turbulence other than the balloon-borne anemometry of wind variations relative to the balloon (YAMANAKA *et al.*, 1985a, b). Using them, YAMANAKA and TANAKA (1984a, b, 1985) detected wind variations associated with gravity waves and turbulence in the middle stratosphere near SBC. The balloon-borne anemometers for PPB-borne use should be slightly improved for a very long duration flight. In addition, data discrimination, compression and accumulation should be also developed.

A recent numerical study by TANAKA *et al.* (1987) suggests that a predominant activity of orographic gravity waves and their breakdown is crucial in the high-latitude general circulation. We have never compared such a numerical result with the actual atmosphere, since the circumpolar survey of the Arctic gravity wave activities by instrumented balloons is not permitted by many reasons including non-technical ones. Hence, the Antarctic is only one area to confirm the numerical results in the actual atmosphere.

4. Summary

The mean circumpolar period and small north-south drift in the summer Antarctic stratosphere were calculated using the southern-hemispheric data obtained during MAP. Early-January 30–40 km flights are best for PPB, and they will make a 12–25 day westward circumpolar flight and arrive again in the neighborhood of the Syowa Station within a latitudinal drift of ±1°. The drift is almost due to the planetary waves, and the contribution of local gravity waves is negligible.

Our second choice is mid-winter flight (June–August), of which the circumpolar period and drift are roughly 2–4 day eastward and ±2°. However, the surface weather conditions in mid-winter are too bad to launch balloons, so that this choice is practically unfeasible. The wind reversal seasons (October–November and February) are inadequate for circumpolar flights.

Utilizing the PPB project, trajectory analysis and balloon-borne anemometry are promising for researches of the middle-atmosphere dynamics. Although the preparation is not yet completed now, we expect that the results must be fruitful.

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