Rocketsonde Observations of the Middle Atmosphere Dynamics at Uchinoura (31°N, 131°E) during the DYANA Campaign

Part I: Outline of Experiments and Background Conditions

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We describe in this paper preliminary results on the characteristics of the wind velocity and temperature profiles obtained through rocketsonde measurements during the DYANA campaign. The wind velocity profiles in the height region of 20–90 km, obtained with the rocketsondes, were compared with the results simultaneously observed with the MU (middle and upper atmosphere) radar at 60–100 km. The profiles were consistent with each other up to 80 km, when they were smoothed out for a height range of 8 km. While for wind velocity fluctuations with vertical scales of a few km, the rocketsonde results showed significantly larger amplitudes than those obtained with the MU radar above 60 km. Consideration of the vertical wavenumber spectra of the wind velocity fluctuations suggested that the maximum height range of the rocketsonde profile, by which the gravity wave characteristics can be delineated, seemed to be limited only up to about 60 km. The background zonal winds were westward in the stratosphere, but they exhibited large time variations, coinciding with a minor stratospheric sudden warming. The temperature profiles also indicated great variability near the stratopause and in the mesosphere, probably due to the effect of the enhanced activity of planetary waves.

1. Introduction

Through international cooperation, STEP (Solar Terrestrial Energy Program) is currently being conducted in order to obtain a quantitative understanding of the coupling processes between different height regions of the atmosphere through studies on the dominant mechanisms responsible for the energy and mass transfer. Campaign observations of DYANA (DYnamics Adapted Network for the Atmosphere), one of the STEP projects, were conducted in January–March 1990 by means of internationally coordinated rocket, balloon and various ground-based measurements, to which a Japanese group has extensively contributed (OYAMA *et al.*, 1992). All the information concerning the scientific activities conducted by the Japanese group during the DYANA campaign was summarized by OYAMA (1991), who provides the fundamental data-bases as well as a list of participants.

This is the first of two papers on data analysis of the rocketsonde results together with those of observations with the MU (Middle and Upper atmosphere) radar. The primary purpose

of this paper is to present the reliable height range of the rocketsonde profiles, which depends on both the height resolution and the measurement accuracy, and to further describe the background conditions of the middle atmosphere during the DYANA campaign, in particular, the effects of a minor stratospheric sudden warming. While the companion paper (TSUDA *et al.*, 1992) presents the characteristics of gravity waves, describing the height variations of the gravity wave energy in terms of the vertical wavenumber spectrum, and the effect of the stratopause structure upon the upward propagation characteristics of gravity waves.

In this paper we first present, in Section 2, a brief description of the rocketsonde experiment, including the fundamental data analysis procedure. Section 3 is devoted to comparison of the wind velocity profiles between the rocketsonde and MU radar results. In Section 4, the background conditions of the wind fields and the temperature structure are discussed in relation to the minor stratospheric sudden warming.

2. Experimental Techniques

During the DYANA campaign, series of rocket experiments were carried out at the Kagoshima Space Center of the Institute of Space and Astronautical Science (ISAS) at Uchinoura, Japan ($31^{\circ}15' \text{ N}$, $131^{\circ}05' \text{ E}$), in the period from the middle of January to the end of February 1990. Two different kinds of rocketsondes, Super Loki and Viper, were employed, the former being equipped with a datasonde including a temperature sensor, and the latter with a passive falling sphere (hereafter referred to as DUD and DUS, which stand for DYANA-Uchinoura-Datasonde, and DYANA-Uchinoura-Sphere, respectively).

The range and azimuthal and elevation angles of the descending datasonde and falling sphere were determined with a ground-based radar, the results being recorded on magnetic tape every 100 ms. After averaging the results for 1 s, the location of the rocketsonde was calculated in the Cartesian coordinate system. Horizontal wind velocity was delineated from the time derivatives of horizontal displacements of the rocketsonde.

On the other hand, the temperature values obtained with DUD were transmitted to a ground station by means of a transponder. The fundamental data-processing procedures for the rocketsonde experiments were described in detail by SCHMIDLIN (1986). Both wind velocity and temperature profiles were obtained with DUD in the height range of about 20 km to 55–75 km. While only the wind velocity was measured with the DUS, although the maximum height was extended to about 110 km. The profiles were smoothed out so as to give the wind velocity and temperature with a height interval of 300 m. In total, five DUD and three DUS were successfully launched, as listed in Tables 1 and 2, respectively. Note that DUD-2 unfortunately failed to measure the temperature profile.

In cooperation with the rocket experiments, various ground-based observations were simultaneously carried out. In particular, the wind profiles in the troposphere-lower stratosphere (5–22 km altitude) and mesosphere (60–90 km), with height resolutions of 150 m and 600 m, respectively, were observed with the MU radar at Shigaraki, Japan ($34^{\circ}51' \text{ N}$, $136^{\circ}06' \text{ E}$). The basic procedures for the MU radar observations were summarized, for example, by TSUDA *et al.* (1989). Note that meteor echoes were also used for profiling the wind fields at 76–100 km, the observation technique being previously described by NAKAMURA *et al.* (1991).

Table 3 summarizes the dates and the height ranges of the MU radar experiments. The profiles were collected for only 45 min–2 hrs on 7 days in the lower atmosphere, while the mesosphere observations were continued for 6–12 hrs on 11 days, and for 1–2 hrs on 3 days.

Table 1. Details of Super Loki datasonde experiments.

No.	Launch time		Height range	
			Wind	Temperature
DUD-1 (SL-2)	21:10 LT	17 Jan. 1990	21–71 km	20–55 km
DUD-2 (SL-3)	21:10 LT	20 Jan. 1990	23–74 km	Failure
DUD-3 (SL-4)	21:25 LT	29 Jan. 1990	20–55 km	32–56 km
DUD-4 (SL-5)	21:10 LT	31 Jan. 1990	17–52 km	22–56 km
DUD-5 (SL-6)	21:10 LT	5 Feb. 1990	20–53 km	22–54 km

Table 2. Details of Viper falling sphere experiments.

No.	Launch time		Height range
DUS-8 (VP-5)	21:00 LT	17 Feb. 1990	18–107 km
DUS-9 (VP-7)	21:00 LT	24 Feb. 1990	15–111 km
DUS-10 (VP-8)	21:00 LT	26 Feb. 1990	20–107 km

Table 3. List of MU radar observations.

Date/1990, Local time*	Height (km)	Resolution		Remarks
		Height (km)	Time (s)	
Jan. 16 11:22–17:01	60–98	600	150	Meteor Wind Observation
17 07:02–17:00	60–98	600	150	
18 07:03–17:01	60–98	600	150	
19 07:02–16:33	60–98	600	150	
Feb. 6 06:03–17:00	60–98	600	150	
7 06:02–17:00	60–98	600	150	
9 06:02–17:01	60–98	600	150	
10 12:13–12:59	5–24	150	150	
12 12:01–12:59	5–24	150	150	
15 12:00–14:00	5–24	150	150	
17 12:04–13:00	60–98	600	150	
16:54–17:59	5–24	150	150	
19 10:01–12:02	5–24	150	150	
24 12:14–13:40	60–98	600	150	
17:38–18:37	5–24	150	150	
19:05–23:02	76–100	2000	1800	
26 09:57–12:15	5–24	150	150	
	60–98	600	150	
Mar. 13 06:02–18:01	60–98	600	150	
14 06:03–18:01	60–98	600	150	
15 06:03–18:00	60–98	600	150	
16 06:03–16:13	60–98	600	150	

*Local time = UT + 9 hours.

3. Comparisons of the Wind Velocity Profiles between the Rocketsonde and MU Radar Observations

Although the height profiles of the wind velocity were obtained with DUS up to over 100 km, all the observed height range may not be used for studies on the middle atmosphere dynamics, since a rocketsonde does not normally follow the motions of the ambient atmosphere at high altitudes.

Detailed comparisons of the profiles between the DUS soundings above about 60 km and the MU radar observations in the mesosphere were carried out in order to estimate the reliable height range and the measurement error of the DUS soundings.

In Fig. 1, we present horizontal wind profiles obtained on the DUS-9 sounding at 2100 LT, and the wind velocity averaged over 1–2 hours for the MU radar observations on 24 February 1990. The DUS profiles were obtained after low pass filtering with a cut-off of 15 s on the time series of the record sampled every 1 s. The descending speed of a falling sphere exponentially decreases below about 80 km height with decreasing altitude, which is, for example, as great as about 500 and 200 m/s at about 80 and 60 km altitude, respectively. So the vertical resolution of smoothed profile depends on the altitude, which was estimated to be 8 and 3 km at 80 and 60 km, respectively. Comparing the profiles of the rocketsonde and MU radar observations in Fig. 1, we found that both zonal and meridional wind velocities agreed

Fig. 1. Vertical profiles of (left) northward and (right) eastward wind velocity observed with the DUS-9 sphere and the MU radar on 24 February 1990. The thick solid line indicates the sphere data, while the other lines represent MU radar observations, i.e., the MST observations in the height regions of 5–22 and 60–90 km for 1738–1838 LT and 1214–1340 LT, respectively (thin solid lines), and the meteor wind observation for 1908–2302 LT (thin dashed line).

well up to about 80 km, despite the differences in the observation locations and intervals, the latter differing as much as about 8 hr.

It can be generally understood that the accuracy of wind velocity measurements seems to become worse as the altitude increases, since the motion of a falling sphere does not necessarily follow the atmospheric winds at high altitudes. HYSON (1968) suggested that the difference between the horizontal speed of a falling sphere and the motion of the ambient atmosphere exponentially decreases, and further defined a range constant, corresponding to the vertical distance, in which the difference in the horizontal speed decreases by a factor of e .

The range constant, h , can be written as $h = 2m/(C_d S \rho)$, where m , C_d , S and ρ denote the mass, cross sectional area and drag coefficient of the sphere, and the air density, respectively. The h value becomes as high as about 20 and 2 km at 80 and 60 km, respectively, for a standard falling sphere with a diameter of 1 m and a weight of 160 g (SCHMIDLIN, 1986). Therefore, although the comparison of the profiles obtained with DUS and the MU radar showed reasonable agreement up to about 80 km with the height resolution of 8 km, we should keep in mind that DUS soundings at a high altitude could involve discrepancy from the actual wind fields due to the fairly large value of the range constant.

We now examine the altitude range where the wind fluctuations can be delineated reliably enough for the analysis of gravity waves. After the DUS profiles had been averaged, equally spaced data samples with an interval of 300 m being produced, a low pass filter with a cut-off of 3 km was applied so as to increase the confidence by reducing the random noise. Using these data, we further extracted the wind velocity fluctuations, as illustrated in Fig. 2, using a band pass filter with a pass band of 4–6 km for both the DUS and MU radar results. We can recognize that the DUS data in the height range above 70 km cannot be utilized for gravity wave analysis, because the fluctuations were not realistic, compared with the MU radar data. In the altitude

Fig. 2. Band-passed (4–6 km) fluctuations of (right) zonal and (left) meridional wind velocities observed with the MU radar (thin lines) and a falling sphere (thick lines) on 24 February 1990.

range of 50 to 70 km, the amplitudes of the fluctuations obtained with DUS for meridional components increased with height from about 2 to 14 m/s, exceeding the MU radar results by about 6 m/s above 60 km, while the zonal components showed reasonable coincidence with the MU radar profile up to 65 km.

Within the altitude range of the direct comparison of the profiles between the DUS and MU radar experiments, we were unable to clearly define a reliable height region suitable for the analysis of the wind velocity fluctuations with scales down to a few km. Therefore, we describe these fluctuations in terms of the vertical wavenumber spectra, whose statistical characteristics were empirically well established through a theoretical model as well as the earlier results (e.g., MURAYAMA *et al.*, 1992; TSUDA *et al.*, 1992).

Figure 3 shows the vertical wavenumber spectra of horizontal wind velocity observed with the MU radar in comparison with the model spectrum, which shows the fairly representative behavior in each height region. That is, the mesospheric spectra agreed well with the model values in the wavenumber region of 1.1×10^{-4} – 7×10^{-4} c/m for both the zonal and meridional components, while the amplitudes of the stratospheric spectra were smaller than the model values by a factor of about 3–10, the slope being less than -3 , respectively.

Figure 4 presents vertical wavenumber spectra determined from the DUS-9 data in the two height regions of 50–60 and 56–66 km, which partially overlapped each other. The spectra of the zonal and meridional components in the 50–60 km height range showed amplitudes smaller than the model values by a factor of about 7 and 2, respectively, and slightly gradual slopes of about 1.7 for both components, which reasonably interpolated the spectra obtained with the MU radar in the regions above and below. On the other hand, in the height range of 56–66 km, the spectral amplitudes of the zonal component were larger than the model values by a factor of about 7, although the meridional component appeared to be similar to the model. Therefore, we could consider that the wind velocity profiles above about 60 km obtained in the DUS experiments may not be used for the analysis of gravity waves.

To summarize the direct comparisons between the DUS and MU radar results, the wind

Fig. 3. Vertical wavenumber spectra derived from the MU radar data obtained on 24 February 1990. The zonal and meridional components are presented as solid and dashed lines, respectively.

Fig. 4. The same as Fig. 3 except that the wind velocities were observed with DUS-9 and at the height ranges of 50–60 (left) and 56–66 km (right).

velocity profiles with DUS can be used for profiling the mean winds up to about 80 km, when the fine structures with vertical scales less than about 8 km were smoothed out. While the maximum height for studies on the gravity wave characteristics, having scales down to a few km, should be restricted to about 60 km, below which the height resolution was reasonably good for describing the characteristics of gravity waves. Note, however, that the latter was inferred from the results of investigation on the behavior of the vertical wavenumber spectra.

It is noteworthy that the systematic error in wind velocity determinations is normally larger at higher altitudes, furthermore, the height resolution becomes exponentially worse with altitude, since it is inversely proportionally to the air density (e.g., SCHMIDLIN, 1986). However, both the amplitudes and vertical scales of the dominant gravity waves also increase with altitude, as described in MURAYAMA *et al.* (1992) in detail, therefore, the height variations in the measurement accuracy with rocketsondes are not a significant problem for describing the vertical structure of the wind velocity fluctuations in the middle atmosphere.

4. Background Conditions of the Middle Atmosphere during the DYANA Campaign

4.1 General characteristics of wind velocity and temperature profiles

We present in Fig. 5 the observed profiles of horizontal wind velocity in the height range of 20 to 60 km, eight profiles for the eastward and northward wind velocity being shown.

The general behavior of the zonal component can be described as follows: its amplitude was fairly small at the lowest altitude, i.e., at 20 km, it became westward, and then reversed direction toward the east at higher altitudes. The meridional component showed small amplitudes below 35 km throughout the observation period, and was generally southward (equatorward) above 35–40 km, the amplitudes ranging from 5 to 15 m/s.

Simultaneously illustrated in the bottom panel of Fig. 5 are the model zonal winds taken from the CIRA1986 model at 30°N, where the profiles were linearly interpolated from the monthly values by assuming that the model represents the profile in the middle of each month.

Fig. 5. Profiles of northward (top) and eastward (bottom) wind velocity obtained with rocketsondes at 20–60 km. Note that the vertical reference line, indicating 0 m/s for each profile, shifts according to the date of the year of the experiment. The zonal winds taken from the CIRA1986 model in January and February at 30°N are also indicated by thin lines.

Note that we present only the zonal mean values of the CIRA1986 model, although the model includes the climatological patterns of the planetary waves with longitudinal wavenumbers 1 and 2, which, however, normally have significant effects on the zonal winds in winter.

In fact, a part of the discrepancy in the zonal winds between the observations and the model can be explained by considering the behavior of planetary waves. In particular, the westward winds demonstrated in the stratosphere in Fig. 5, for instance, on 17 and 20 January, seemed to be caused by the effect of planetary waves with longitudinal wavenumber 1, whose effect frequently becomes dominant in winter, enhancing the Aleutian high (e.g., MATSUNO and SHIMAZAKI, 1981).

However, the most striking feature of the zonal winds during the DYANA campaign seemed to be represented by the fairly large time variations. In order to exhibit more clearly these variations, Figs. 6 and 7 show contour plots of the zonal and meridional winds, respectively, obtained by combining the profiles in Fig. 5 and the MU radar results in the

Fig. 6. Contour plot of the eastward wind velocity after processing with a low-pass filter; having a cut-off at 8 km, for each sounding shown in Fig. 5, combined with the daily mean profiles observed with the MU radar on 16–19 January, and 6, 7 and 9 February 1990.

Fig. 7. The same as Fig. 6 except for the northward wind velocity.

mesosphere, where a low-pass filter with a cut-off at 8 km was applied in order to remove small scale fluctuations caused by gravity waves.

The altitude of the zonal wind reversal from westward toward the east was 40–45 km at the beginning of the observation period, but it rapidly dropped to below 40 km in the sixth profile and became as low as 35 km at the end of February. Moreover, although the height region of the westward winds was extended to 20–50 km on 17 January 1990, it was only 20–35 km at the end of the observation period.

While for the third and fourth profiles in Fig. 5 obtained on 29 and 31 January, the westward winds in the stratosphere almost completely disappeared, but they became slightly eastward in the entire height range, exhibiting the discontinuous time variations of the zonal winds in comparison with other profiles. Note that the discontinuous behavior of the zonal winds at the end of January 1990, being deviated from the general tendency of the zonal winds, can be more easily recognized in Fig. 6. The time variation of the profiles, excluding the third and fourth ones, suggests that the phase speed of the downward progression of the zonal wind reversal is to be about -0.3 km/day. The contour plots for the meridional winds in Fig. 7 generally reflect the variation of the zonal winds. In particular, southward winds of more than 15 m/s were detected at the end of January, which coincides with the discontinuous behavior of the zonal component in Fig. 6.

The temperature profiles during the first half of the DYANA campaign period are illustrated in Fig. 8, being derived from the four DUD soundings listed in Table 1. The zonal mean profile taken from the CIRA1986 model in January at 30°N is also plotted in Fig. 8 for reference. Below about 40 km the first profile agreed reasonably well with the model, although fluctuations were recognized, while the other three profiles showed smaller temperature values than the model by 5–10 K. Moreover, the altitude region with the lower temperature expanded from 22–35 km on 29 January to 22–40 km on 31 January, and further to 20–41 km on 5 February.

The maximum temperature in each profile was detected at 45–50 km, but the location of the stratopause cannot simply be determined because of the complicated structure, exhibiting many peaks and dips. In addition, the temperature profiles in the mesosphere involved quite large fluctuations. For example, by comparing the profiles collected on 29 and 31 January, it

Fig. 8. Temperature profiles obtained with the Super Loki rocketsondes at 20–60 km. The successive profiles are shifted by 30°C in the left panel, while all the profiles are simultaneously illustrated in the right panel in order to show the time variations. The thin lines show the CIRA1986 model profile in January at 30°N .

can be recognized that there was a large decrease in the mesospheric temperature profile within the three day period, the maximum difference between the extreme values being about 20 K above 48 km.

4.2 *Effect of a minor stratospheric sudden warming*

It was reported that a minor stratospheric warming, accompanied by a significant temperature increase at 60°N, occurred at the beginning of February 1990 (HIROOKA *et al.*, 1992). Although the direct manifestation of a stratospheric warming is normally confined to the high latitude region (e.g., ANDREWS *et al.*, 1987), its effect can reach down to the middle and low latitudes (for example, at 30°N), as reported during major warmings (KANZAWA, 1980; GILLE and LYJAK, 1984), or in the numerical model for a minor warming (MATSUNO, 1984).

The profiles on 29 and 31 January were collected in the period just before the onset of the minor warming, while that on 5 February coincided with the beginning of the event. The westward winds, detected on 17 and 20 January well before the minor warming event, were weakened on 29 and 31 January, and the eastward winds appeared.

Investigation of the 10 mb geopotential height maps obtained in the objective analysis conducted at the Japan Meteorological Agency, reported in the data catalogue of the DYANA campaign (OYAMA, 1991), suggests that both the polar vortex and the Aleutian high were stably dominant in the middle of January 1990, producing the very cold winter, but the latter became diminished at the end of January and then recovered in late February. In other words, the present minor warming occurred in such a way that the Aleutian high was weakened for half month, approximately coinciding with the minor warming event, which reasonably explains the changes in the zonal wind structure seen in Figs. 5 and 6.

It is also noteworthy that the expansion of the cold temperature region in the stratosphere below 35 km, as detected in the profiles obtained on 29 January–5 February in Fig. 8, in comparison with that on 17 January, seemed to be explained by the effect of the minor warming. That is, the decrease in the stratospheric temperature seemed to occur at middle latitudes, maintaining the heat balance during the minor warming by compensating for the temperature increase at higher latitudes (e.g., MATSUNO and SHIMAZAKI, 1981).

Using the data-base employed for routine weather prediction, HIROOKA *et al.* (1992) found that the planetary waves with zonal wavenumber 1 were conspicuously enhanced at 60°N from 20 January to 10 February, coinciding with the minor stratospheric warming. Such planetary waves were, at least in part, responsible for a part of the disturbed behavior of the mesospheric temperature fluctuations detected in Fig. 8.

To summarize, the characteristics of the background conditions, which include the structure of the horizontal winds and the temperature, showed the significant variations within the 40 days of the DYANA observation period. The observed variations in the profiles of both the zonal winds and temperature seemed to be caused by the effect of the stratospheric warming, together with the enhanced activity of planetary waves.

5. Concluding Remarks

In this paper we have presented preliminary results on the characteristics of the middle atmosphere dynamics, as revealed by rocketsonde observations conducted eight times at Uchinoura, Japan, during the DYANA campaign period with two different kinds of rockets; a Super Loki equipped with a datasonde and a Viper with a falling sphere.

Although the maximum height range of the falling sphere measurements could be extended up to 110 km, the measurement error increases exponentially with height, therefore, we first investigated the reliable height ranges, comparing the results with the MU radar observations. When the wind velocity profiles observed with the falling spheres were smoothed out with the height resolution of 8 km, they were consistent up to about 80 km height with the MU radar observations. However, when the height resolution was improved to 3 km, the amplitudes detected with the falling spheres showed significantly large values above about 70 km height, compared with the MU radar observations. Investigation of the vertical wavenumber spectrum of the wind velocity, referring to the model spectrum of saturated gravity waves, suggested that the fluctuations with vertical scales larger than a few km in the sphere data were reliable only up to about 60 km.

By combining the rocketsonde results with the simultaneous MU radar observations, the background conditions of the middle atmosphere dynamics during the DYANA period were inferred. At the beginning of the DYANA observation period, the zonal winds were generally westward in the stratosphere, showing the effect of the Aleutian high. However, the behavior of the zonal winds was fairly variable, such that the westward winds were weakened, probably due to the effect of a minor stratospheric sudden warming that occurred at the beginning of February 1990. In addition, the profiles obtained at the beginning of the minor stratospheric sudden warming were discontinuous, compared to the general tendency of the zonal winds. Furthermore, the temperature structure near the stratopause and in the mesosphere was also quite variable, probably due to the effect of planetary waves.

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