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First results obtained with a middle and upper atmosphere (MU) radar

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Abstract—First results have now been obtained with a MU (middle and upper atmosphere) radar which has been in full operation at Shigaraki (34°51′N, 136°6′E). In addition to the basic observation of winds in the mesosophere and stratosphere–troposphere, some novel observations have also been attempted. These initial observational results illustrate the capability of the MU radar for studying middle atmosphere dynamics.

1. INTRODUCTION

The MU (middle and upper atmosphere) radar has just been brought into full operation at Shigaraki (34°51′N, 136°6′E) after a four year construction period. The system has an active antenna array of 475 Yagi's, each of which has a small transmitter–receiver module (Fig. 1). The technical details of the system have been given elsewhere (KATO *et al.*, 1984, FUKAO *et al.*, 1985), but the main specifications are as follows: radar frequency 46.5 MHz with the 1.65 MHz band width giving a maximum range resolution of 150 m; beam width 3.6°. The beam can be steered almost continuously within 30° from the zenith to any direction in each interpulse period (IPP), which is 400 μs at minimum; 1024 levels can be sampled in each IPP; the lowest observable height is 2.0 km.

Some results for the stratosphere–troposphere using a partial system have already been published (KATO *et al.*, 1984). However, for the first time the mesosphere has now come into the region under investigation. It is now widely accepted that MST radars, including the MU radar, are powerful tools for the observation of middle atmosphere dynamics. These ground-based remote sensing facilities are able to give better height resolution than other means, such as satellite observations, and the radar technique has the advantage of producing continuity of observation in time and height. Furthermore, radar observation can be carried out under all weather conditions.

The purpose of this short paper is to introduce this MU radar, which will be one of the outstanding MST radars now in operation in the world. Some of the first results shown here are typical basic wind observations proved by the MU radar, and a few others are of a novel character.

2. MESOSPHERE OBSERVATION

The principle of radar mesospheric wind observation is to track refractive index irregularities which co-move with the local winds. Refractive index irregularities in the mesosphere are caused by atmospheric turbulence which perturbs the height distribution of the ambient electron density distribution (e.g. STOLTZFUS and BOWHILL, 1985). However, for the 2 μs pulses usually used, the radar echo, which is produced by scattering from the irregularities, is only strong enough to be detected between 70 and 80 km. Recently, an attempt has been made to increase this observable height range to 60–85 km by using longer subpulses, such as 8 μs, which have narrower frequency band widths, thereby decreasing background noise. This improvement, however, gives lower height resolution and is not suitable for some experiments, such as detecting short period gravity waves (SATO *et al.*, 1985). Beyond this height range there are meteor echoes which can also be used for wind observation. However, unlike turbulent echoes, meteor echoes were received intermittently and one cannot determine three-dimensional wind velocities from three radial wind measurements obtained by rapidly steering the radar beam in three different directions. We assume the winds to be horizontal and this can be true only for winds which are stationary for a few hours at least. Errors can also arise because of meteor echoes received by the radar side-lobe. However, it is found that for meteor heights averaging over a few hours gives a practical solution to this problem. We have checked that results from the MU radar agree with those given by the Kyoto Meteor Radar which operates at a site several hundred metres away (e.g. TSUDA *et al.*, 1985). This implies that those meteor echoes

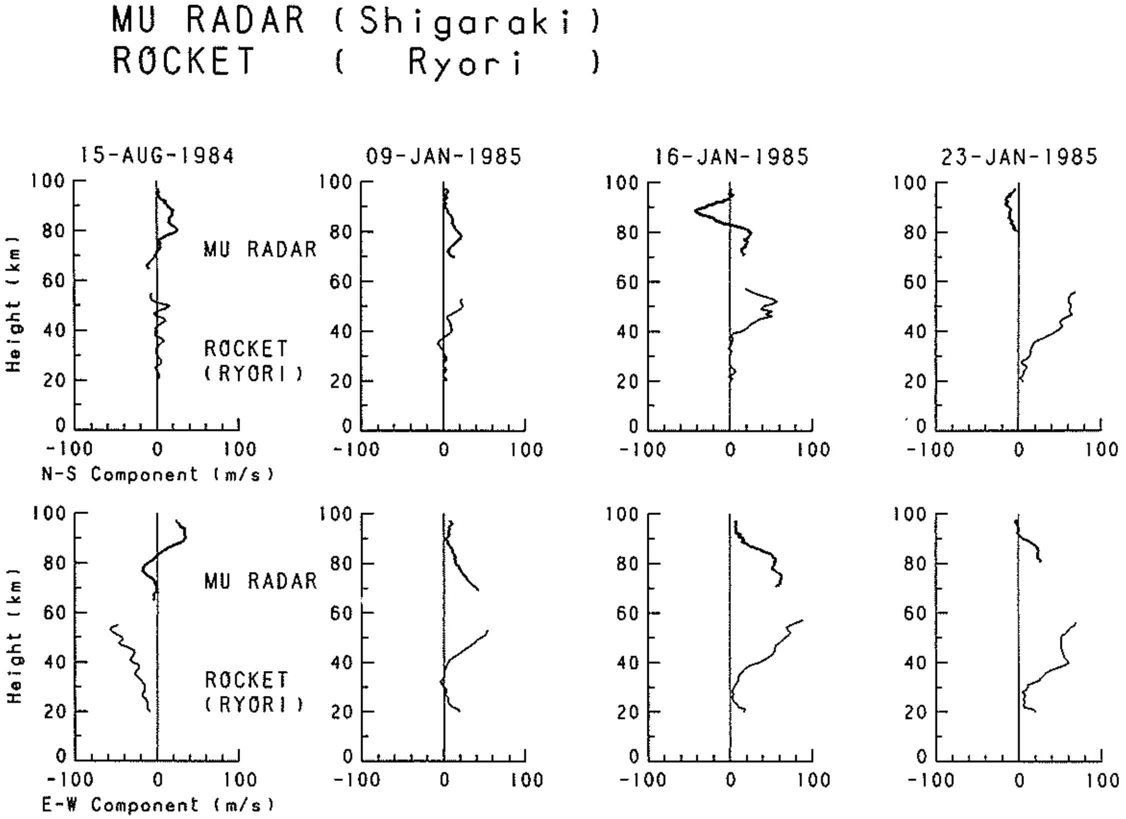


Fig. 2. Mean wind profiles for (top) meridional and (bottom) zonal components in August 1984 and January 1985. The profile below 60 km was obtained by meteorological rocket observation at Ryori, 11.00 h (JST) on each day. The positive value indicates northward and eastward.

which are received by the main beam far outnumber those received by the side-lobes. The meteor echo method, however, cannot be used for the observation of winds fluctuating with shorter periods than a few hours. We are now attempting to determine the arrival direction of each meteor echo by an interferometry technique which can be realized by using some subgroups of the MU radar system. The MU radar consists of 25 subgroups, each of which can operate as independent small radars and this should give a final solution to the problem.

Figure 2 shows some initial results of mesosphere wind observation. The radar beam was steered consecutively in each IPP of 800 μs to three directions; vertical, towards east 10° from the zenith and towards north 10°; a 16-bit complementary code with 2 μs subpulse was used. Each observation has a time resolution of about 2 min and height resolution of 300 m. The velocity in Fig. 2 was averaged for 2 h between 10.00 and 12.00 h JST in the day-time. Together with the MU radar observation, a meteorological rocket observation is shown in the figure, where the wind profile by the rocket observation up to about 60 km is given; the meteorological rocket is regularly launched at 11.00 h JST each week. The MU radar site (Shigaraki) and the rocket launching site (Ryori, 39°N, 141°40′E) are some 800 km apart. Since the observed height range of the MU radar and that of the rocket flights do not overlap, an exact comparison cannot be attempted. However, the zonal wind observed by the MU radar and that by the rockets seem to be in fairly good agreement.

As for gravity wave observations, we have successfully obtained winds which fluctuate with periods of about 9 min. Figure 3 illustrates some results which used the same parameters as those in Fig. 2, except for the beam direction, which was now only towards the south by 10° from the zenith. We filtered the result

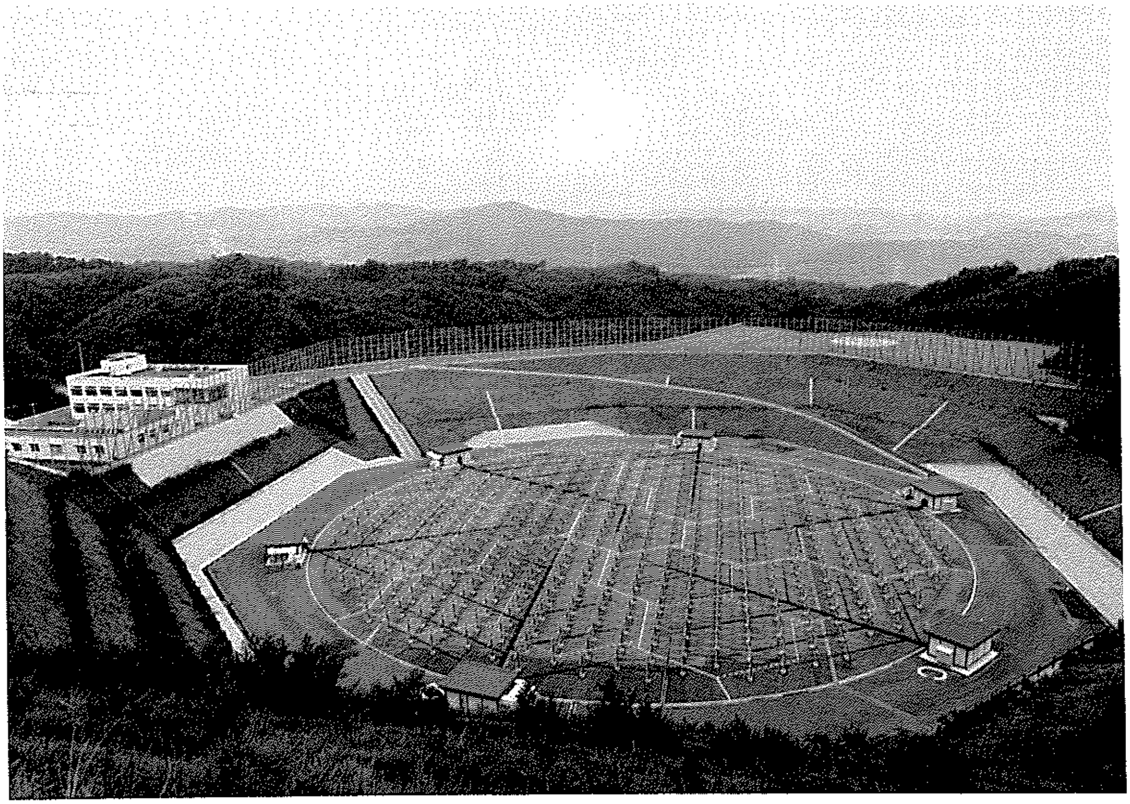


Fig. 1. Bird's-eye view of the MU radar system. The circular antenna area is marked by a white painted line, along and just outside of which the six booths are distributed. These booths accommodate small transmitter–receiver modules of each antenna element. The antenna elements are grouped as marked by white paint in hexagon forms. The antenna level is lower by 15 m than the surrounding hill, on which a metal-net fence 10 m high is built, mainly to avoid the ground clutter due to side-lobe radiation at low elevation angle. The two-storied building on the left on the hill is the control building and next door is the guest house.

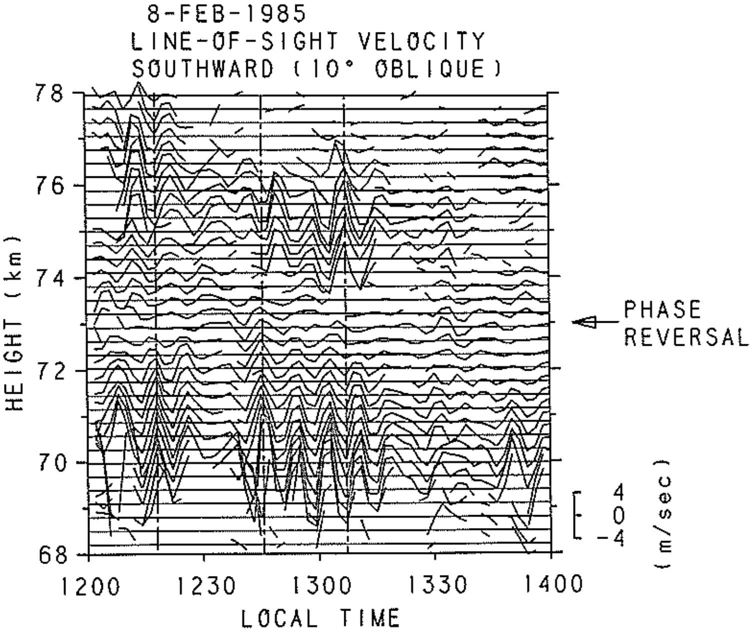


Fig. 3. Gravity wave. The velocity along the radar line-of-sight is shown. The beam is steered by 10° from the zenith towards the south.

with a time resolution of 2 min so as to pick up only fluctuations with periods of 6–16 min. The wave amplitude is found to be minimum around 73 km, at which the phase seems to change very rapidly almost by 180°. The fairly large fluctuation, observed away from and both above and below this transition level, remains almost in phase. Note that similar short period fluctuations were found by Klostermeyer and Ruster (1984), who attempted to interpret the fluctuations in terms of a Kelvin–Helmholtz instability generated also by a strong mesospheric flow as well as by the tropospheric jet stream (Klostermeyer and Ruster 1981).

3. STRATOSPHERE–TROPOSPHERE OBSERVATION

This region gives intense and stable echoes because the echo power received is inversely proportional to the range squared and also the region has intense turbulence, which produces refractive irregularities by turbulent mixing of humidity up to the middle troposphere and beyond this height by turbulent mixing of air density. In this region observation is possible during day and night. Successful wind observations of this region have been made using a partial system which had a radar sensitivity of about 1% of the present complete system (Kato *et al.*, 1984).

We have attempted to observe stratospheric winds over long periods and compare the results with those obtained by rawinsonde at various locations (Table 1). In the radar observation we used a 16-bit complementary code with a 1 μs subpulse, giving 150 m range resolution. The 2 h averaging was done on observed results with 2 min time resolution. This implies the average for 1 h before and after the time of the regular rawinsonde launching at 9.00 and 21.00 h (JST). Approximate agreement between the radar and rawinsonde observation at various sites is found, as shown in Fig. 4. The minor differences are real and due to differences in the site locations. It is to be noted that in Fig. 4(a) the best agreement is with the

Table 1. Location of meteorological stations in Fig. 4.

Station	Latitude	Longitude
Sendai	38°16′N	140°54′E
Wajima	37°20′N	136°50′E
Tateno	36°10′N	140°10′E
Yonago	35°30′N	133°E
Hamamatsu	34°40′N	137°40′E
Fukuoka	33°40′N	130°20′E
Shionomisaki	33°30′N	135°50′E
Kagoshima	31°30′N	130°30′E

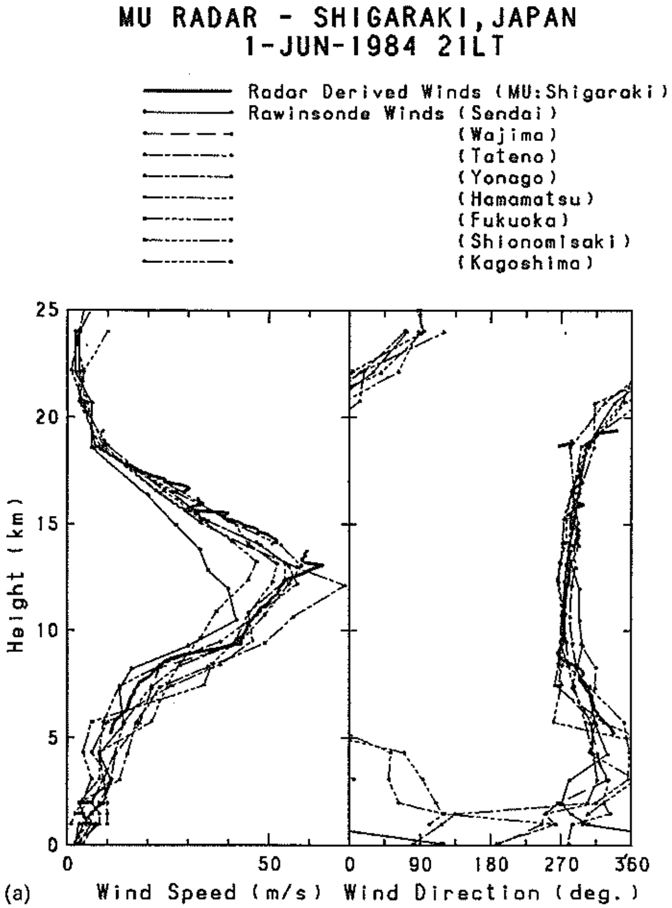
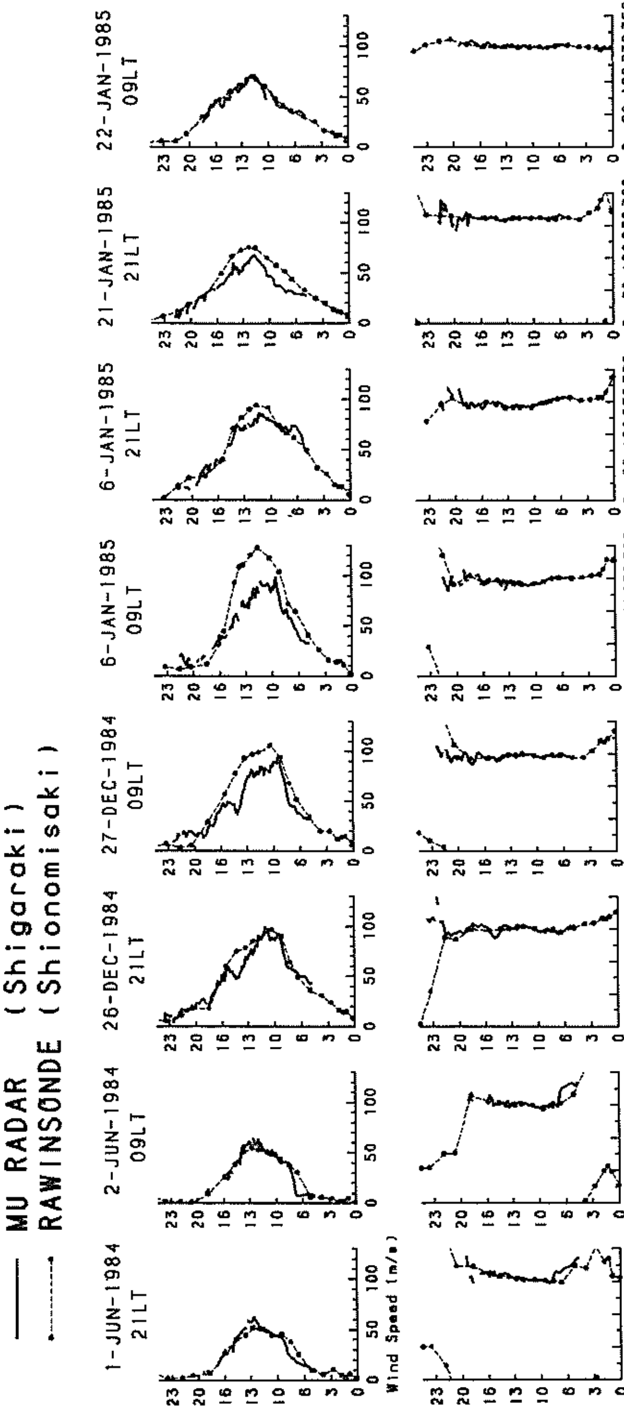


Fig. 4. Troposphere–stratosphere winds. (a) Winds by the MU radar at Shigaraki and rawinsondes at various meteorological stations (Table 1) on 1 June 1984. (b) As (a) except for rawinsonde only at Shionomisaki between June 1984 and January 1985.

Hamamatsu observations, because this site has the same latitude as that of Shigaraki; the jet stream depends mainly on latitude. In Fig. 4(b) we see this prevailing westerly varying from June 1984 to January 1985. It attained a maximum around the beginning of January 1985. Whilst the amplitude at Shigaraki is sometimes smaller than that at Shionomisaki, the direction is always in good agreement between the two sites.

The MU radar is able to detect winds which vary rapidly with time and Fig. 5(a) shows some results which illustrate this. This figure gives the results of four consecutive days observation. The radar beam was steered in IPP of 400 μs among five directions designated (0,0), (0,10), (90,10), (180,10) and (270,10), where the first figure in the bracket gives the azimuth angle in degrees measured clockwise from the north and the second the zenith angle. A 16-bit complementary code with 1 μs subpulse width was used to give 150 m height resolution. Time resolution is about 2 min. This rapid beam steerability is well suited to obtaining wind vectors varying with time. If we use fixed beams by dividing the antenna array into three parts or more, then each part has a wider beam width than that of the total system, thus producing possible errors. Wind vectors in the horizontal plane are shown by arrows, which represent averaged quantities over five consecutive heights and eight consecutive times. Although each quantity is thus obtained from independent (original) data and is independent, the arrows indicate smooth variations of winds both with height and time. In the troposphere the wind vector rotates anticlockwise from southeastward on 15 July to northeastward on 19 July. The phase of the rotation


MU RADAR (Shigaraki)
RAWINSONDE (Shionomisaki)
1-JUN-1984 21LT
2-JUN-1984 09LT
26-DEC-1984 21LT
27-DEC-1984 09LT
6-JAN-1985 09LT
6-JAN-1985 21LT
21-JAN-1985 21LT
22-JAN-1985 09LT
Height (km)
0 3 6 10 13 16 20 23
Wind Speed (m/s)
0 50 100
Direction (degree)
0 90 180 270 360

(b)

Fig. 4 (*contd.*)

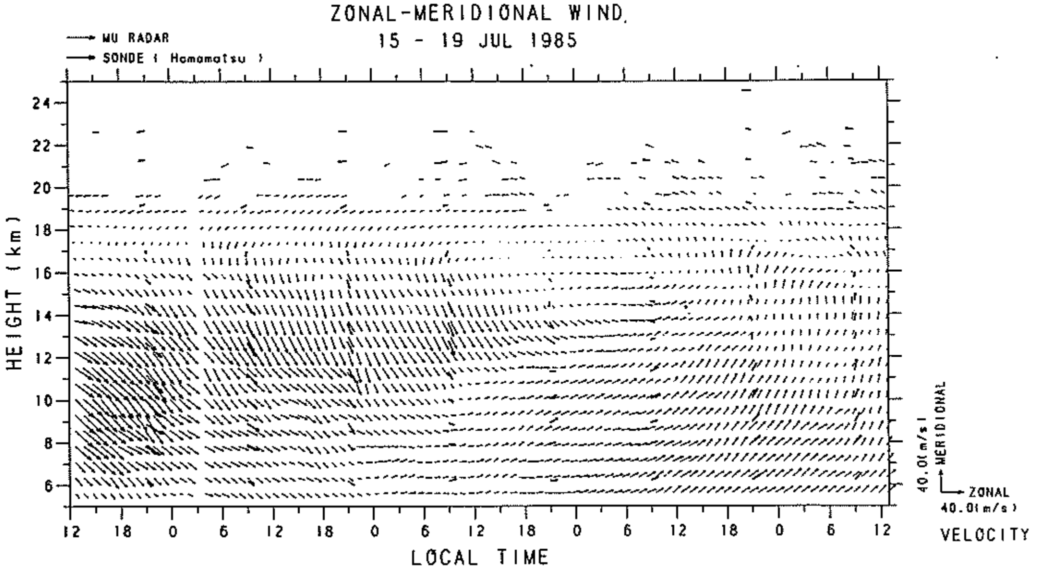


Fig. 5(a) Horizontal wind vector. Thin arrows show winds observed by the MU radar and thick arrows winds by rawinsonde at Hamamatsu. The scale is shown beside the corner (bottom and right) of the diagram. Generally, observation in three different beam directions can decide wind vectors, but observation in more beam directions, such as the present one, better suits varying wind measurements.

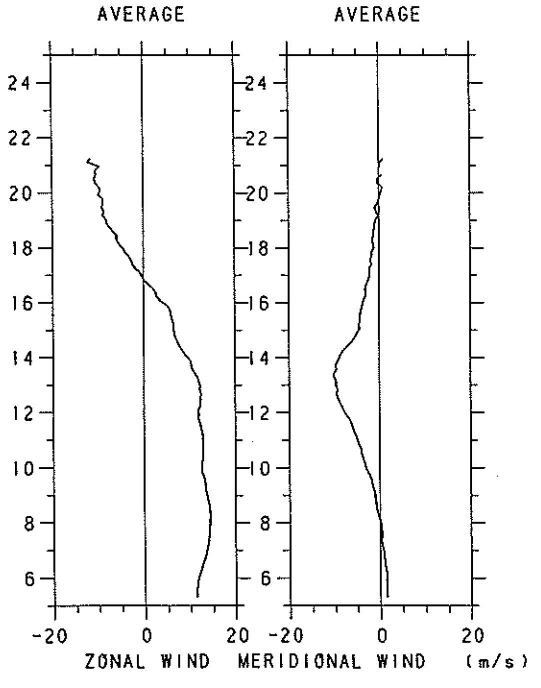


Fig. 5(b). Averaged wind profile. Averaging is for 15–19 July 1986. The positive value is eastward and northward.

moves upwards with time. In the stratosphere (the tropopause being at about 16 km for this period) the rotation is clockwise, although the wind there is very weak. The weather map for this period at 500 mb (about 5.5 km high) shows that a trough passed over Shigaraki just before 15 July and another trough approached on 19 July. The observed tropospheric wind variation seems to be well explained in terms of the geostrophic approximation, considering the trough which is expected to extend upwards with a westward tilt as a planetary wave in westerly (eastward) winds. The observed weak stratospheric wind can be expected from the averaged zonal wind distribution in Fig. 5(b), which shows an easterly (westward) wind above 17 km. Note that planetary waves cannot penetrate into the easterly region. We are now attempting to find fluctuating components as gravity waves in the original data with the 2 min and 150 m resolution. It is possible that gravity waves play a role in stratospheric dynamics similar to that in the mesosphere (Tanaka, private communication, 1986) and this may present interesting future problems for the MU radar.

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