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VHF Doppler Radar Determination of the Momentum Flux in the Upper Troposphere and Lower Stratosphere: Comparison between the Three- and Four-Beam Methods

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ABSTRACT

The vertical flux of horizontal momentum in the upper troposphere and lower stratosphere can be measured by VHF Doppler radars using the mesosphere–stratosphere–troposphere (MST) radar technique. Two methods have been used: one using three beams, one vertical and two oblique, and the other using four beams, two pairs of oblique beams symmetrically offset from the vertical. According to theory the four-beam method should be more accurate, but because some radars do not have the capability of using the four-beam method, it is important to assess the accuracy of the three-beam method. In this study the rapid steerability of the Japanese MU radar was used to make three- and four-beam measurements simultaneously. It is found that the three-beam flux agrees with the four-beam flux only for long-period fluctuations. For shorter periods a systematic error is caused by wind fluctuations with wavelengths that are comparable with the separation between the beams (2–7 km in this study).

In this study, performed during summer at 35°N latitude, it is found that the momentum flux due to long-period fluctuations is caused primarily by synoptic-scale or mesoscale disturbances, while short-period flux may primarily be related with intense vertical air motion. Thus, during these observations, the contribution of gravity waves seemed to be unimportant.

1. Introduction

The divergence of momentum flux (or Reynolds stress) gives friction (acceleration or deceleration) to synoptic or planetary-scale atmospheric motions (Holton, 1972). Particularly important is the vertical convergence of the horizontal flux that causes the net acceleration of the general mean circulation. Recently, it has been suggested that internal gravity waves play an essential role in transporting momentum flux from the lower atmosphere upward into the mesosphere (e.g., Lindzen, 1981; Holton, 1982; Matsuno, 1982). However, there was not any practical means of testing this model by direct measurement of the momentum flux until Vincent and Reid (1983) proposed a method that utilizes the MST (mesosphere–stratosphere–troposphere) radar technique (see Balsley and Gage, 1980, 1982; Gage and Balsley, 1984; Green et al., 1979; Harper and Gordon, 1980; Larsen and Röttger, 1982; Röttger, 1984, for reviews).

In order to measure the component of momentum flux in a given vertical plane Vincent and Reid's method requires that the radial velocity be measured simultaneously in two directions symmetrically offset from the vertical in that plane. The momentum flux is proportional to the difference between the variances of the radial velocity in the two directions. By making measurements in two orthogonal planes, the vector momentum flux can be calculated. Thus, their method requires that a radar have four beams in two pairs. This is called the "four-beam method."

Unfortunately, some MST radars either cannot direct beams symmetrically about the zenith or else they cannot do so simultaneously. Instead, some of these radars have attempted to measure the momentum flux in a vertical plane by using only one oblique and a vertical beam (e.g., Avery et al., 1985). When this is done in two vertical planes, it uses three beams, so it will be referred to as the "three-beam method."

Although developed independently, both methods are special cases of the Velocity Azimuth Display (VAD) technique that has been formerly employed by meteorological Doppler radars (e.g., Lhemitte, 1968; Wilson, 1970). A description of the VAD technique may be found in Wilson and Miller (1972). This technique has also been used to determine turbulence fluxes by meteorological Doppler radar (Kropfli, 1986).

The MU (middle and upper atmosphere) radar can steer its antenna beam every interpulse period (IPP)

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(Kato et al., 1984; Fukao et al., 1985a,b). This satisfies the condition of simultaneity of measurement mentioned above. Also, utilizing this fast beam steerability, the momentum flux in the upper troposphere and lower stratosphere can be determined by the three- and four-beam methods during the same time interval. This capability is used in the present paper to determine the extent to which the three-beam method can be used for momentum flux measurements.

The momentum flux can also be measured with nonsymmetric beam configurations if three coplanar beams are available (Reid, 1987). However, since this sort of beam steerability is not necessarily found at all MST radars, only the conventional three- and four-beam methods will be discussed. This paper will be concerned principally with the technical aspects of the methods. Detailed discussion of the physical meaning of the observed momentum flux is beyond the scope of the present paper.

2. Method

Vincent and Reid (1983) first measured the vertical flux of horizontal momentum in the mesosphere using two narrow beams symmetrically offset from the zenith in a vertical plane, as shown in Fig. 1a. Following Vincent and Reid (1983), the relevant theory is outlined below.

The instantaneous radial velocities in the two beams, V_1 and V_2, are given as

$$V_1 = u_1 \sin\theta + w_1 \cos\theta$$
$$V_2 = -u_2 \sin\theta + w_2 \cos\theta \qquad (1)$$

where u_i and w_i ($i = 1, 2$) are the horizontal and vertical wind velocities, respectively, and θ is the zenith angle. The fluctuating velocities are calculated from the instantaneous velocities by subtracting the mean values averaged over the whole period of observation as follows:

$$V_i' = V_i - \overline{V_i}, \qquad (2)$$

where the prime denotes a fluctuating velocity and the overbar denotes the time average. The difference between the time-averaged variances of V_1' and V_2' is

$$\overline{V_1'^2} - \overline{V_2'^2} = \overline{(u_1' \sin\theta + w_1' \cos\theta)^2} - \overline{(-u_2' \sin\theta + w_2' \cos\theta)^2}$$
$$= (\overline{u_1'^2} - \overline{u_2'^2}) \sin^2\theta + (\overline{w_1'^2} - \overline{w_2'^2}) \cos^2\theta$$
$$+ 2(\overline{u_1'w_1'} + \overline{u_2'w_2'}) \sin\theta \cos\theta, \qquad (3)$$

where u_i' and w_i' ($i = 1, 2$) are, respectively, horizontal and vertical wind fluctuations around the mean values. If the statistics of the fluctuating velocities are assumed to be independent of horizontal position, so that the mean values $\overline{u_i'^2}$, $\overline{w_i'^2}$ and $\overline{u_i'w_i'}$ are identical in both beams, the momentum flux per unit mass is given as follows:

$$\overline{u'w'} = (1/2 \sin 2\theta)(\overline{V_1'^2} - \overline{V_2'^2}). \qquad (4)$$

The momentum flux per unit volume is obtained by multiplying by the atmospheric density. In the following the momentum flux per unit mass will be used unless otherwise noted. The above assumption is true for wind fluctuations caused by gravity waves. To measure both zonal and meridional momentum fluxes two pairs of beams are employed.

On the other hand, for the three-beam method the vertical and one oblique beam are used as shown in Fig. 1b. The wind field is assumed to be horizontally uniform in the region where the antenna beams are directed. Then, the fluctuating horizontal wind u' in the plane including both beams is determined by using V_1' and w_0' as follows:

$$u' = (V_1' - w_0' \cos\theta)/\sin\theta. \qquad (5)$$

By using (1), u' becomes

$$u' = u_1' + (w_1' - w_0') \cot\theta. \qquad (6)$$

The fluctuating vertical wind w' is directly measured by the vertical beam as

$$w' = w_0'. \qquad (7)$$

Thus, the momentum flux is defined by

$$\overline{u'w'} = \overline{u_1'w_0'} + (\overline{w_1'w_0'} - \overline{w_0'^2}) \cot\theta. \qquad (8)$$

This equation means that correlations of fluctuating wind components at separate positions, which vary with horizontal scales of wind variations, contribute to the estimated momentum flux. It is noted that (8) is an approximation to the exact value obtained for a coherent gravity wave by Reid (1987). The oblique beam is directed eastward or northward to measure the corresponding component of momentum flux.

Because gravity waves are free to take a range of wavenumbers for a given wave frequency, the separation of horizontal scales cannot be achieved by filtering velocity time series, unless there is independent evidence for a relationship between these wave parameters. This indicates that if a significant proportion of the momentum flux is contributed by the waves with short horizontal wavelengths, this beam configuration is of limited use for this measurement (Reid, 1987). Thus, the momentum flux calculated from quantities measured in spatially separated volumes are only correct for scales equal to, or much larger than, the volume separation (Reid, 1987). This error is not met in the four-beam method because mean volumes are identical in both beams. Various uncertainties involved in the three-beam method are discussed theoretically for a single coherent gravity wave in comparison to the four-beam method by Reid (1987).

3. Experiment

The MU radar, located at Shigaraki, Japan (34°51′N, 136°06′E), is a 46.5 MHz radar using an active phased array system (Fukao et al., 1985a,b). The peak and

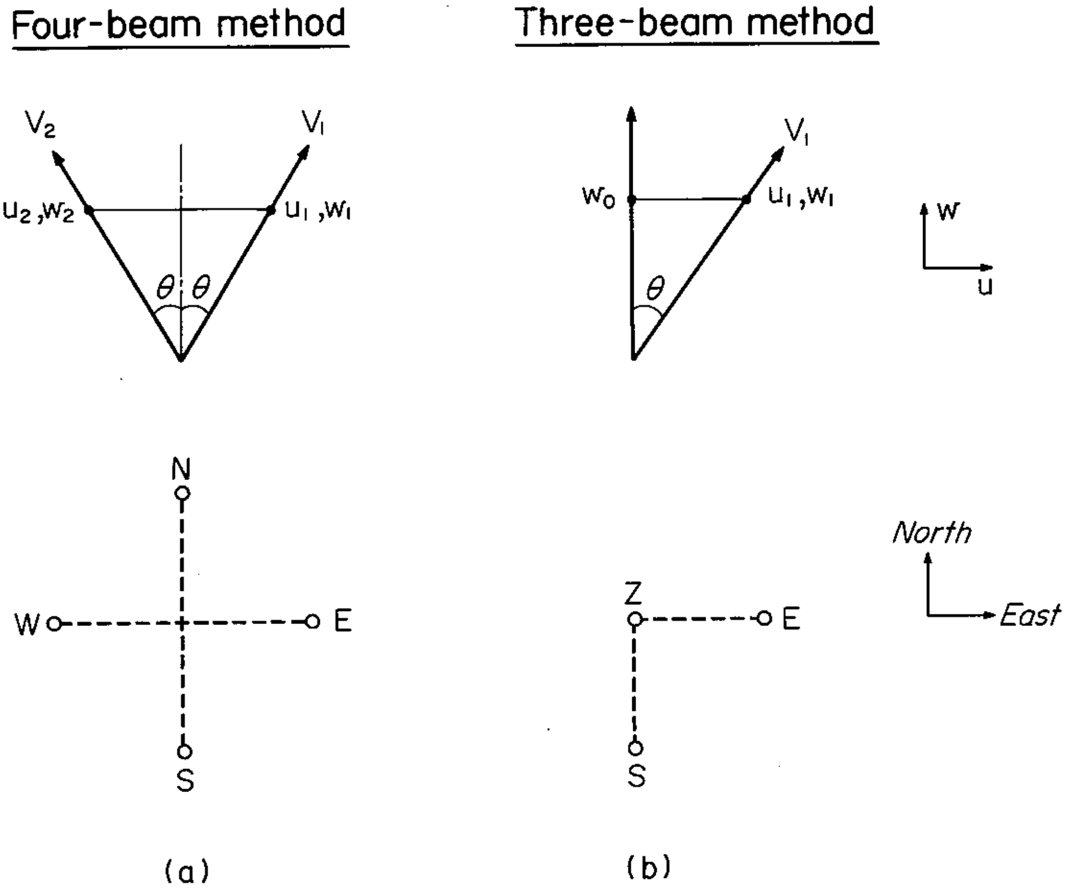

FIG. 1. Geometry of the antenna beams for (a) four- and (b) three-beam determinations of momentum flux by MST radars. Side and plan views are given on the top and bottom, respectively. Beam positions are indicated by N (northward), W (westward), S (southward), E (eastward), and Z (vertical, upward).

average radiated power of the system are 1000 and 50 kW, respectively. The antenna aperture is 8330 m^2, providing a one-way beam width of 3.6° in half-power width. This system makes it possible to steer the antenna beam up to 30° from the zenith in each interpulse period (IPP).

The observations were conducted during a 4-day period from 1211 JST 15 July to 1210 JST 19 July 1985 (JST is Japan standard time). The antenna beam was steered every IPP to five directions, N, W, S, E and Z, shown in Fig. 1. The zenith angle of the oblique beams was 10°. The horizontal distance from the beam Z to other beams ranges from 1 to 3.5 km in the height range considered (5.32 to 20 km). The transmitted pulse is a 16-element complementary code with 1 μs pulse width, corresponding to 150 m height (range) resolution. The use of this coded pulse limits the lowest height of observation to 5.32 km above the ground level (375 m above sea level). The radial wind velocity is obtained approximately every 2.5 min in the five beam directions.

Using the three beams (E, S and Z), the zonal and meridional momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ are calculated using the three-beam method. Also, two pairs of beams, W and E, and N and S, are used for the four-beam method. Since the beams are sequentially steered to the five directions, the momentum fluxes are simultaneously determined by the two methods. Since there is a slight difference in height between points at the same range in the vertical and oblique directions, the vertical velocities are interpolated to the corresponding oblique range by applying a spline-function approximation.

4. Results

a. *Mean wind field*

According to the 500 mb weather charts (approximately 5.5 km above sea level) a trough passed by Shigaraki before 15 July followed by a ridge on 17 July; another trough then approached on 18 July.

Figure 2 shows the field of horizontal wind vectors obtained by the MU radar during this period in the eastward (zonal) and northward (meridional) 2-D coordinate system (Kato et al., 1986). The wind data are averaged over five consecutive heights (750 m) and ap-

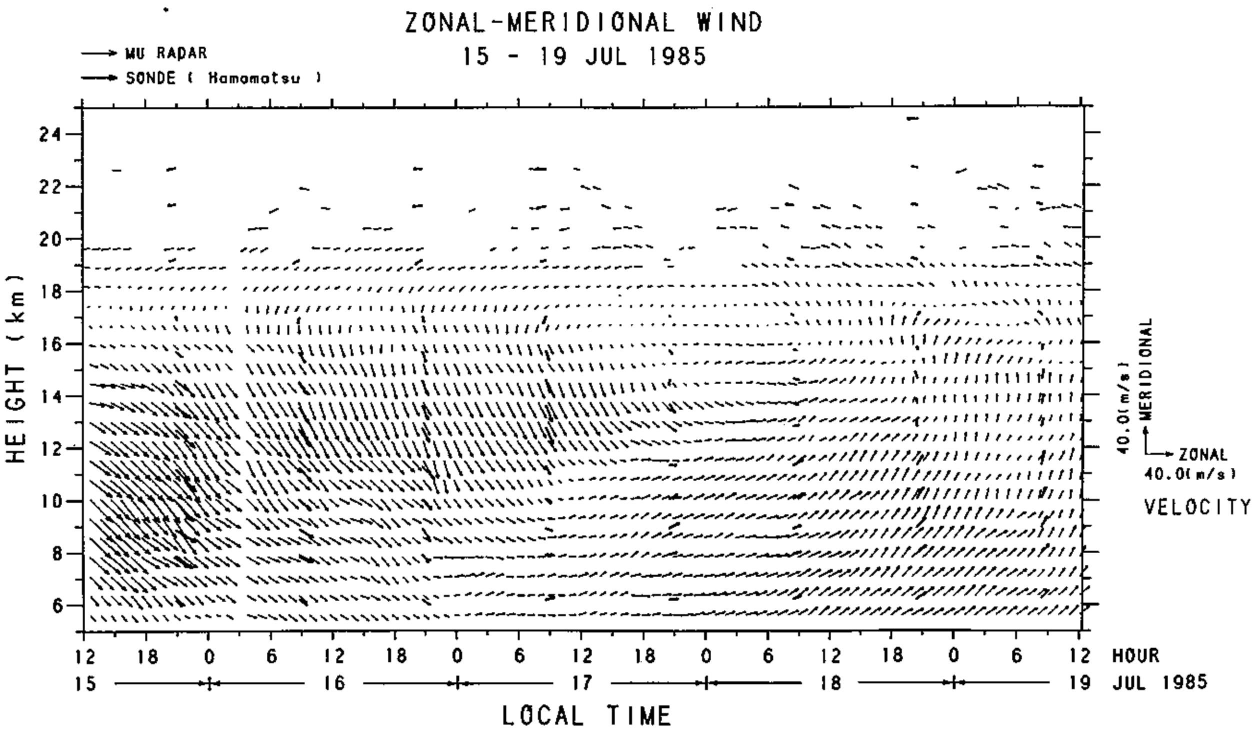

FIG. 2. Horizontal wind vectors observed during 15–19 July 1985. Thin arrows show winds observed by the MU radar at Shigaraki (34°51′N, 136°06′E) while thick arrows show winds obtained by the routine rawinsonde observations at Hamamatsu (34°40′N, 137°40′E). The velocity scale is given on the right-hand side.

proximately 60 min. In the troposphere the wind vector rotates counterclockwise with time from northwesterly (southeastward) on 16 July to southwesterly (northeastward) on 19 July. The rotation is clockwise with increasing height. In the stratosphere the rotation is clockwise, although the wind there is fairly weak.

The thick vectors indicate the horizontal wind obtained by routine rawinsondes launched daily at 0900 and 2100 JST by the Japan Defense Agency from Hamamatsu (34°40′N, 137°40′E), approximately 150 km east of Shigaraki. The agreement between the two measurements is generally excellent, considering the distance between the two observational sites.

b. Mean momentum flux

It is generally regarded that atmospheric zonal motions are composed of a longitudinally averaged part (zonal mean) plus deviations from the average (perturbations) superimposed on the zonal mean. The divergence of momentum flux as well as heat flux associated with the perturbations are important sources for the mean zonal flow. These flows are parameterized as linear functions of the zonal mean, and implemented in a linear model for the zonal mean circulation.

The present observation is made from a fixed ground station. The wind variation is not the spatial variation from the mean value, but instead it is defined as the temporal variation from the mean value calculated by averaging over the entire observational period. Thus, the mean momentum flux observed by this technique is a time mean value obtained from a fixed station. The averaging is made over the whole observational period, i.e., from 1211 JST 15 July to 1210 JST 19 July 1985.

The mean momentum flux together with the variance of wind fluctuations is shown in Fig. 3, where, henceforth, v', u' and w' are, respectively, meridional, zonal, and vertical wind fluctuations around the mean values. All quantities except w' are obtained by the four-beam method. At almost all heights of observation, there are significant upward fluxes of eastward and southward momentum. (Conventionally, the gravity waves that transport the momentum flux are assumed to be generated in the lower part of the atmosphere.)

The vertical flux of each momentum is evaluated by the use of atmospheric density calculated from climatological values of pressure and temperature of rawinsonde observation at Hamamatsu as shown in Fig. 4. The absolute values are typically 0.1–0.2 nm^{-2}. This is smaller than the value of 0.5 nm^{-2} obtained by Lilly and Kennedy (1973) in the lower stratosphere from wintertime observation over the eastern slope of the Rocky Mountains.

The body forces or the vertical convergences of the horizontal momentum fluxes are also estimated in Fig. 4 as

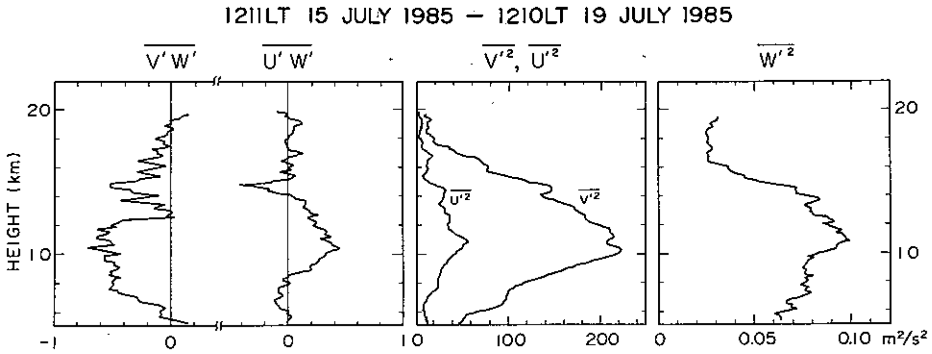

FIG. 3. Four-day average of momentum flux and variance of wind fluctuations determined from the unfiltered wind data. All estimates except the variance of vertical wind fluctuation are determined by the four-beam method.

$$F_v = -\frac{1}{\rho}\frac{d}{dz}(\rho\overline{v'w'}) \tag{9}$$

and

$$F_u = -\frac{1}{\rho}\frac{d}{dz}(\rho\overline{u'w'}) \tag{10}$$

where ρ is the atmospheric density. Other terms related to the net acceleration of the mean flow such as the vertical divergence of the Eliassen–Palm flux are not considered in order to avoid complexity, since the spatial scales of the wind fluctuations are not observed at a fixed ground station. Therefore, the body forces calculated above do not necessarily mean the net acceleration of the mean flow, but it will be very important to estimate the extent that the observed quantities give the stress to the mean flow. The body force is calculated for the smoothed curves of the momentum fluxes filtered to vertical scales larger than 1.5 km.

By using both components it is possible to infer the total body force. Absolute values of approximately 5–25 m s^{-1}/d are found, with considerable variation in magnitude with height. The maximum value in the zonal plane is approximately 15 m s^{-1}/d around a height of 13 km, where the vertical gradient of the momentum flux is a maximum. Though this is quite large, the zonal wind does not appear to vary in response to the body force (Fig. 2).

Figure 5 shows the cospectrum between v' and w' as a function of period at each altitude calculated by using (4). This shows the relative contribution of different period-ranges to the momentum flux. The primary contribution seems to come from a period-range

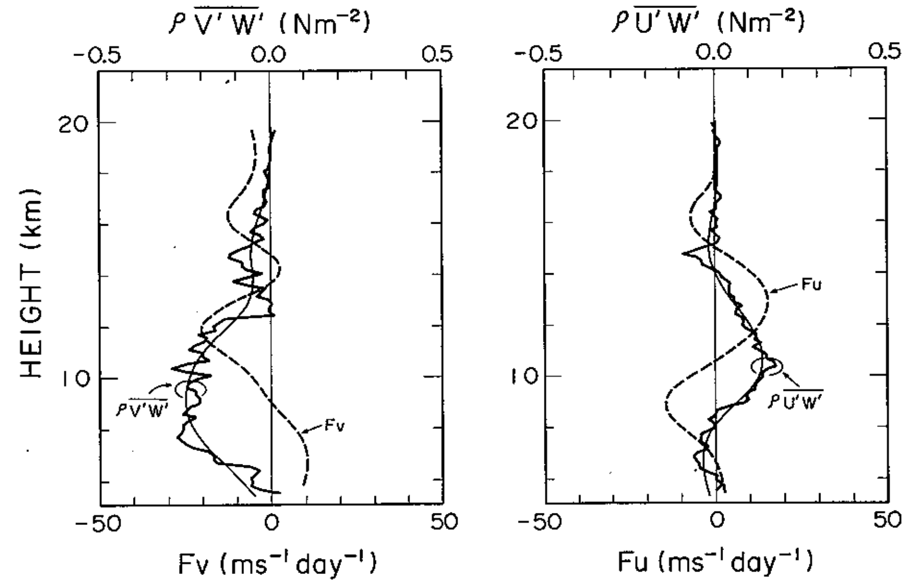

FIG. 4. Four-day average of momentum flux per unit volume and body force. Thin solid lines show the momentum flux filtered to vertical scales longer than 1.5 km. Left: Meridional component; right: zonal component.

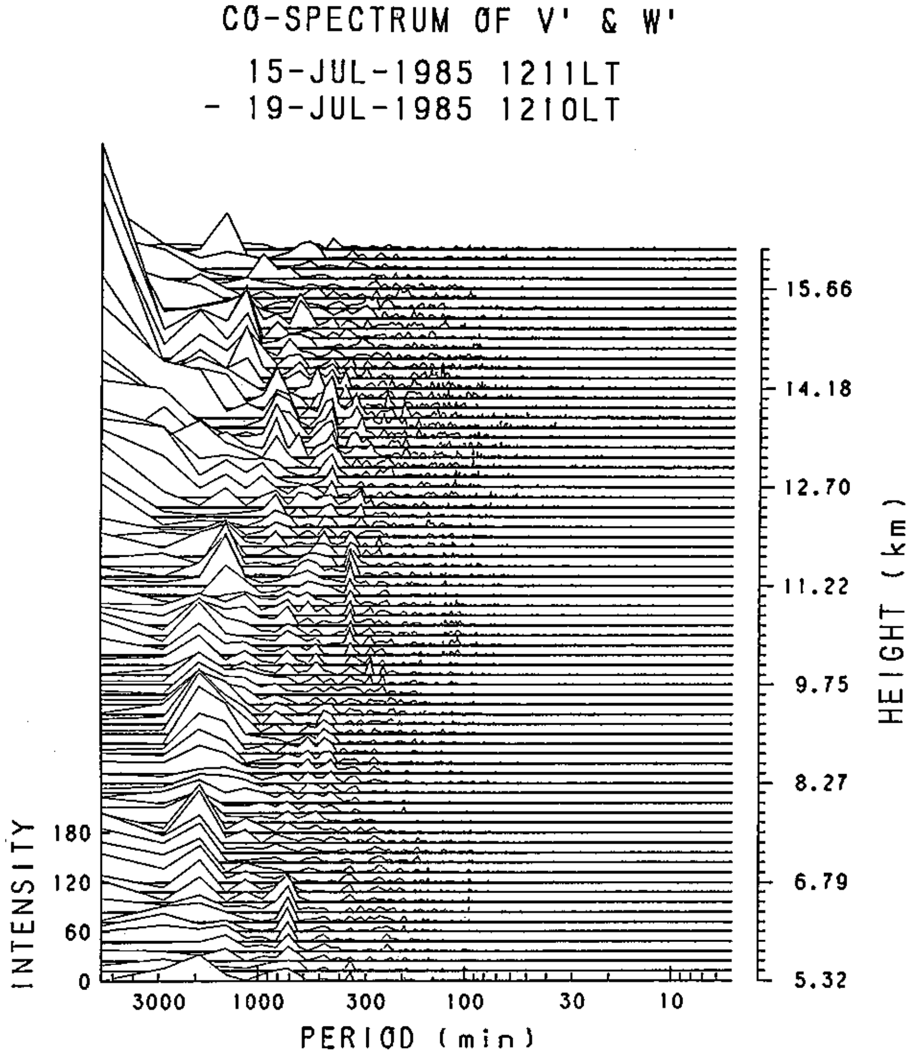

FIG. 5. Four-day average of cospectrum between v' and w' vs height. The intensity scale is shown only for the spectrum at 5.32 km.

larger than approximately 300 min or 5–6 h. Similar result is also found in the cospectrum between u' and w'. This result suggests that the observed momentum flux primarily consists of longer-period components.

The influence of synoptic-scale or mesoscale disturbances is apparent in Fig. 6, where the temporal variations of momentum flux and wind variance at a height of 5.91 km are shown. The solid lines are the results for the unfiltered wind data, while the broken lines and chains are for wind data on time scales longer and shorter than 6 h, respectively. The longer-period component of v'^2 is predominant on 16 and 18–19 July, because the meridional wind changes from northerly (southward) to southerly (northward) during this period. The shorter-period component always dominates in w'^2, which is probably related to intense vertical air motions as discussed below.

The momentum flux has been determined to be due, primarily, to long-period fluctuations as is apparent in the top two panels. The momentum flux at longer periods is especially enhanced when troughs passed by Shigaraki.

c. Comparison between the three- and four-beam methods

In this subsection, the mean momentum fluxes determined by the two methods are compared in period-ranges both longer and shorter than 6 h. The fluctuating wind data are numerically filtered prior to calculating the momentum flux.

The left panel of Fig. 7 shows the momentum flux calculated from fluctuating wind components with periods longer than 6 h. The solid lines are for values determined by the four-beam method, while broken lines are for those by the three-beam method. For both methods, the results are essentially the same as for the

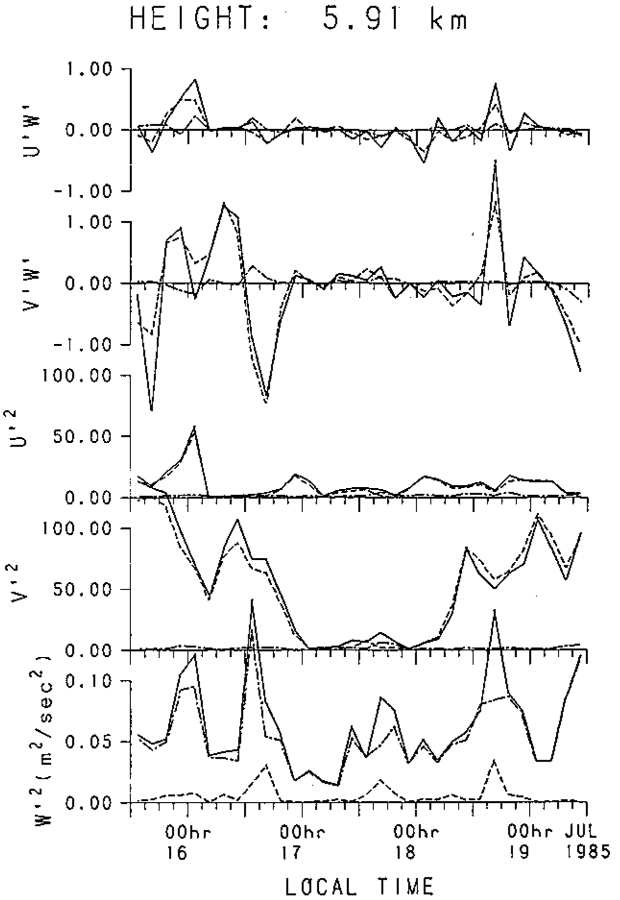

FIG. 6. Temporal variation of the momentum flux and variance of wind fluctuations at a height of 5.91 km. Solid lines show the results for the unfiltered wind data, while dashed and dash-dot lines are for wind data on time scales longer and shorter than 6 h, respectively.

unfiltered, four-beam method shown in Fig. 3. This indicates that the unfiltered results are dominated by the longer-period components, and that for such waves, which tend to have horizontal wavelengths considerably larger than the distance between the oblique beams (2 to 7 km), the three-beam method gives good results.

The right panel of the same figure is the variance of the vertical wind fluctuation with periods longer than 6 h. In the four-beam method, the vertical wind is given by the arithmetic mean of the radial velocities in the four-beam directions divided by $\cos\theta$. As expected for longer-period wind fluctuations, the vertical wind directly measured by beam Z and the arithmetic mean wind agree very well.

In Fig. 8, the results for the period range less than 6 h are presented. The three-beam method gives a more negative momentum flux in both components: the four-beam value is nearly zero in the height range considered, while the three-beam value shows a systematic deviation on the order of -0.1 m^2 s^{-2}.

The right panel of the same figure shows that the vertical wind fluctuations differ significantly between the two methods, while the variance of the directly measured vertical wind is very near to that of the unfiltered data shown in Fig. 3. Small-scale wind fluctuations are averaged out in taking the arithmetic mean value for the four-beam method, while for direct measurement all fluctuations are included in the vertical beam. The difference is considered to reflect the spatial variation of the vertical wind in scales on the order of horizontal distance between the beams.

The difference between the momentum flux determined by the three- and four-beam methods may be partly referred to this spatial variation of vertical wind. The difference is larger at heights where shorter-period fluctuations are predominant (or where $\overline{w'^2}$ is large). The momentum flux obtained by the three-beam method is probably a "noise" caused by vertical wind fluctuations with horizontal scales less than the beam separation (Fukao et al., 1986). According to the theoretical analysis by Reid (1987), scales up to ten times the beam separation still produce incorrect values of $\overline{u'w'}$ and $\overline{v'w'}$.

A small error in antenna pointing or, more likely, an inclination of baroclinic surfaces due to synoptic- or mesoscale disturbances could result in a small specular signal component, and transform u and v into the measured w. These effects are unfortunately not yet clear. Figure 9 shows a time–height section of the vertical wind data observed by the vertical beam Z. The average value is almost zero in the height range observed. As shown in this diagram, any wavelike wind change is, in general, not typical, but the vertical wind variation is fairly coherent in the vertical direction over a wide height range up to the tropopause around 16 km (see Fig. 10a). Considerably intense updrafts are observed in columnar regions in a short span of time at, e.g., 1600 JST 15 July, 0000 and 1300 JST 16 July, and 1200 JST 18 July, while a considerably large downdraft is observed at 1800 JST 17 July. The mechanism to generate these strong vertical winds is not yet understood.

There is no direct way to show that the four-beam method measures the true momentum flux. However, as mentioned in section 2, the four-beam method is expected to be less sensitive to the spatial variation of wind fluctuations than the three-beam method. Since the above experimental difference between the two methods is consistent with the theoretical expectation (Reid, 1987), it is considered that the four-beam method gives more reliable estimates of the momentum flux than the three-beam method.

Comparing the results for the four-beam method shown in Figs. 7 and 8, it is found that during this period the horizontal momentum consists primarily of long-period components rather than short-period components. The horizontal momentum in this height range is presumably generated by synoptic-scale or

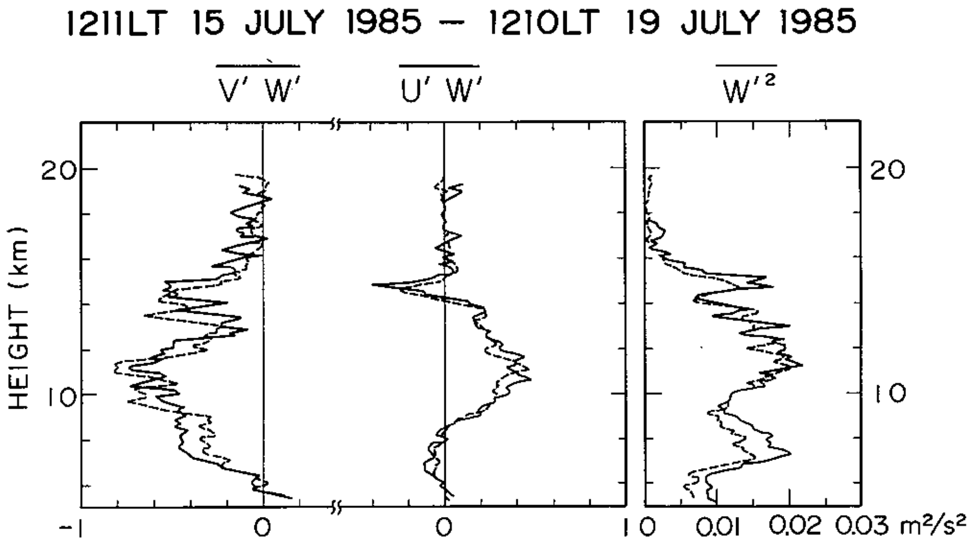

FIG. 7. Four-day average of momentum flux and variance of vertical wind fluctuation calculated from the filtered data with periods longer than 6 h. Solid lines are for the values determined by the four-beam method, while broken lines are for those by the three-beam method. Note that the abscissa scale of the variance is $^{12}/_{5}$ times larger than that of Fig. 3.

mesoscale disturbances rather than by traveling gravity waves. This result is in contrast to the mesospheric results obtained by Vincent and Reid (1983) and Reid (1986), where the flux in short periods less than 1 h preferentially causes the body force.

d. Momentum flux in the short-period range

The $\overline{w'^2}$ in the period range shorter than 6 h decreases with height in the 10–20 km range as shown in Fig. 8. Also, $\overline{v'^2}$ in the same period range decreases with height from approximately 3 m^2 s^{-2} at 10 km to 1 m^2 s^{-2} at 20 km, while $\overline{u'^2}$ decreases from about 2.5 to 1 m^2 s^{-2} in the same height range. (Neither $\overline{v'^2}$ nor $\overline{u'^2}$ is included in Fig. 8.) This suggests that the fluctuation energy dissipates during upward propagation. If this decrease is caused by the wave-mean flow interaction, $\overline{v'w'}$ and $\overline{u'w'}$ should change with height. Nevertheless, $\overline{v'w'}$ and $\overline{u'w'}$, determined by the four-beam method, show little change with height (Fig. 8). This indicates that both v' and u' correlate very little with w', suggesting that the major part of this wind fluctuation does not originate from gravity waves.

Figure 10a shows a time–height section of $\overline{w'^2}$ calculated from the data in Fig. 9. Fairly large variance values which extend up to the tropopause, detected by the rawinsonde, are observed in columnar regions when an intense updraft or downdraft is observed in Fig. 9. According to the weather charts, moderate cumulus clouds were observed near the MU radar site during

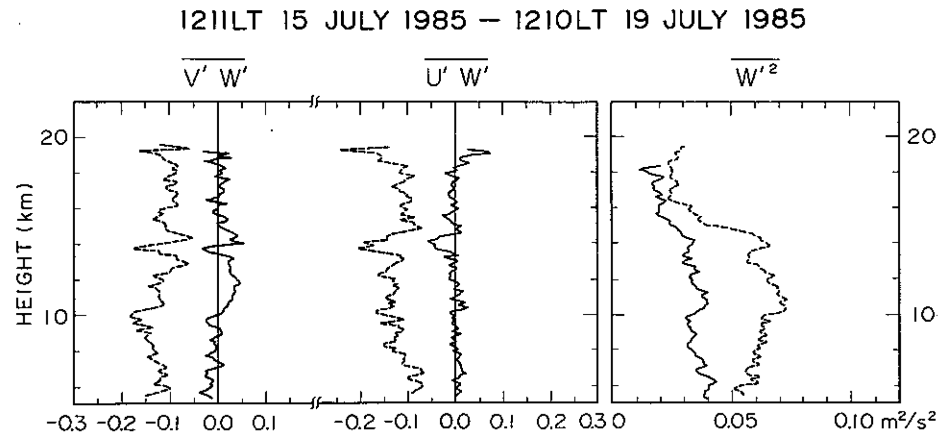

FIG. 8. As in Fig. 7 except for the filtered wind data with periods shorter than 6 h. Note that the abscissa scale of the momentum flux is $^{10}/_{3}$ times larger than that of Fig. 3.

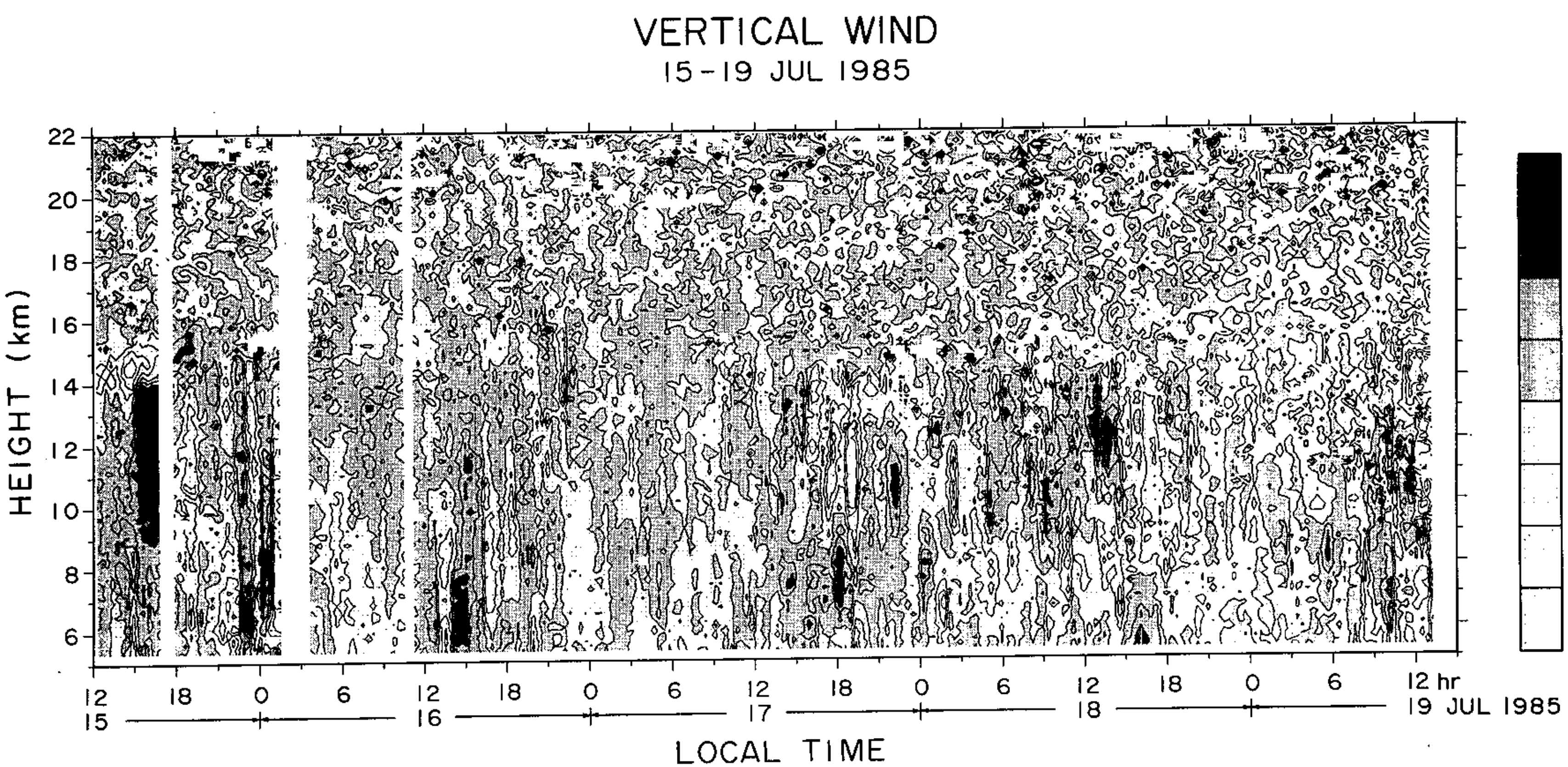

FIG. 9. Time-height section of the vertical wind observed by the vertical beam Z. The wind data are averaged over approximately 25 min.

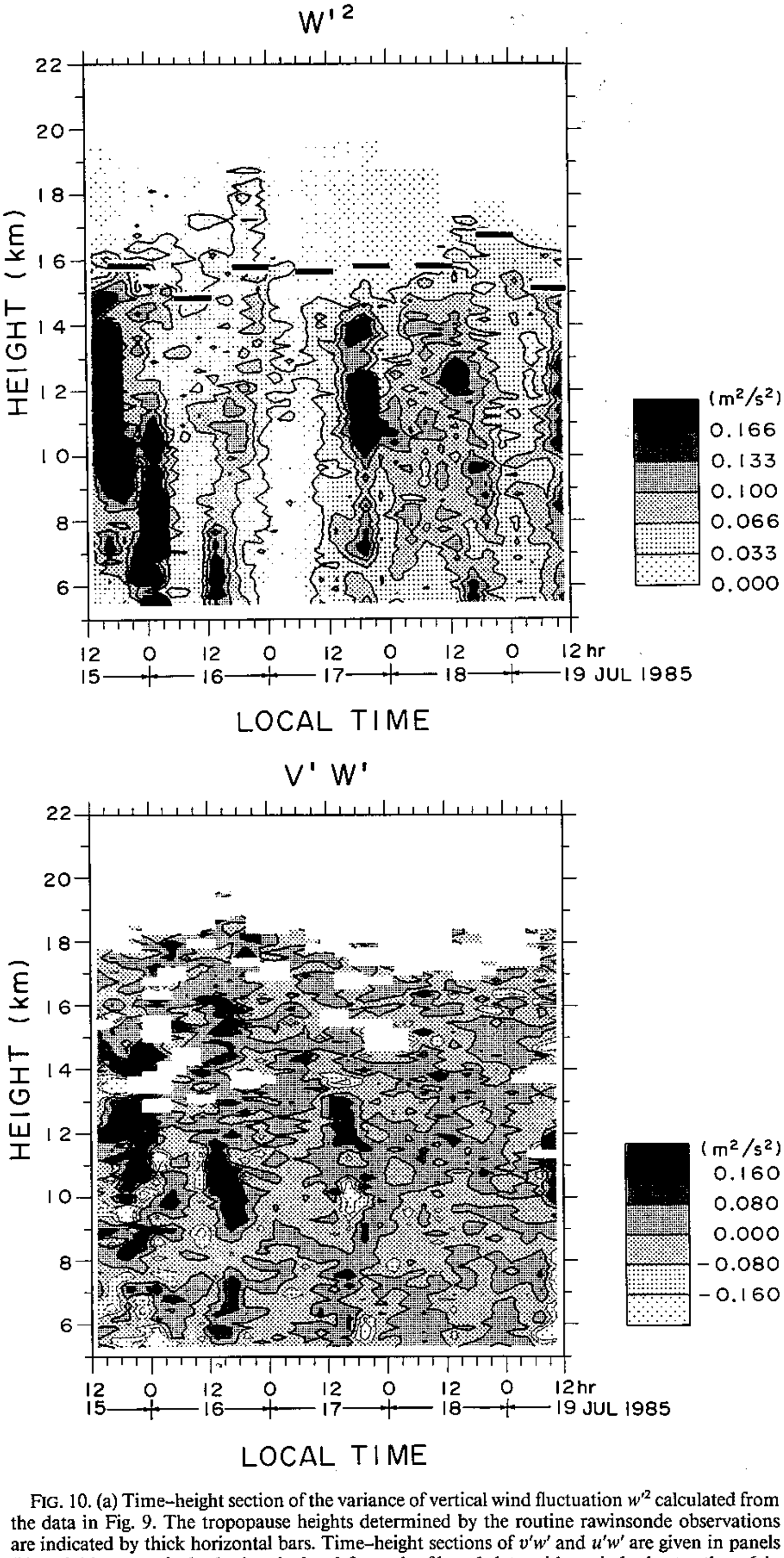

FIG. 10. (a) Time–height section of the variance of vertical wind fluctuation w'^2 calculated from the data in Fig. 9. The tropopause heights determined by the routine rawinsonde observations are indicated by thick horizontal bars. Time–height sections of $v'w'$ and $u'w'$ are given in panels (b) and (c), respectively, both calculated from the filtered data with periods shorter than 6 h. Thick lines demarcate both the positive (upward) and negative (downward) momentum flux.

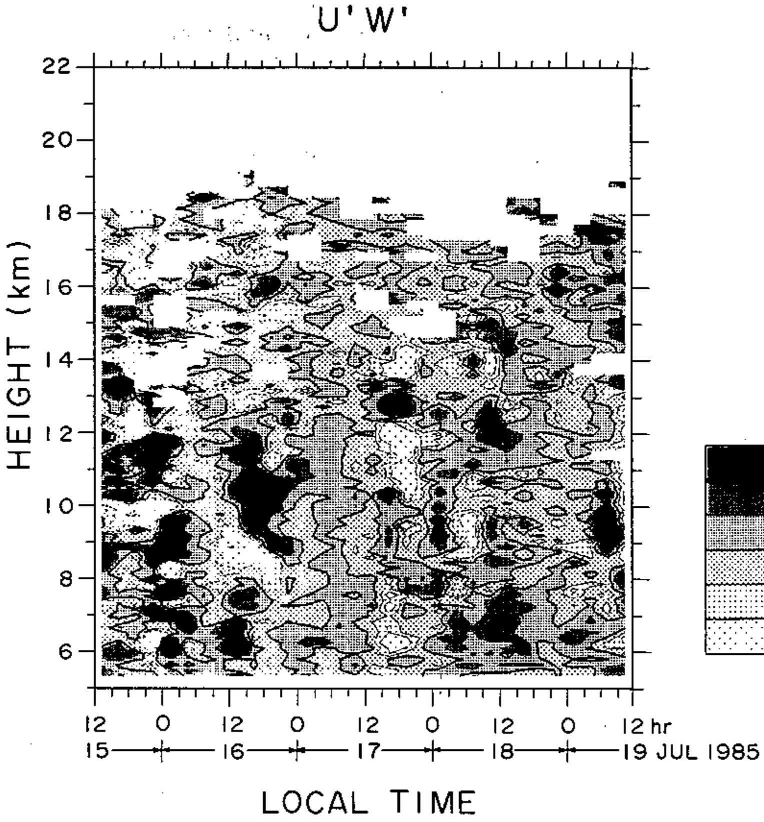

FIG. 10. (*Continued*)

these periods. Thus, some of this columnar structure is considered to be produced by convective air motion. This large columnar structure is not so significant in the similar diagrams for v'^2 and u'^2.

Figures 10b and c are the time–height sections of $v'w'$ and $u'w'$ for the period range less than 6 h. The fairly large upward momentum flux presumably has its principal origin in the intense vertical air motion. The upward momentum flux temporarily exceeds 0.1 $m^2 s^{-2}$ when moderate convective motions are observed in panel a. Large momentum flux is generally observed up to the top of the large convection regions, and negative momentum flux is sometimes observed. This is presumably caused by random wind variations occurring over the MU radar site. The momentum flux also changes with height, suggesting that the local acceleration due to the momentum-flux deposit cannot be disregarded. In this observation, the contribution of traveling gravity waves does not seem to be significant in this height range but is probably effective above about 18 km where the mean wind changes from westerly (eastward) below 18 km to easterly (westward) as shown in Fig. 2. Temporal variation of the momentum flux is really interesting and should be investigated further in relation to the gravity wave parameters in the near future.

e. Spatial variability of the vertical wind

To determine the wind vector by the MST radar technique the wind field is assumed to be horizontally uniform in the region where the antenna beams are directed (e.g., Balsley and Gage, 1980). However, the preceding result suggests that this assumption is not always true.

Figure 11 compares the directly measured vertical wind $w(1)$ with $w(4)$ by the four-beam method at a height of 6.64 km. The number of measurements used is 2279. (One measurement is obtained in approximately 2.5 min.) The gradient (grad) of linear regression line is 0.829, while the cross-correlation coefficient (σ) between $w(1)$ and $w(4)$ is 0.799. Similar results are also found at other heights.

In Fig. 12 height profiles of σ are shown for the unfiltered (raw) data, 12-data averaged (~30 min), and 24-data averaged (~1 h) together with that for data filtered to shorter than 30 min. The longer the averaging, the larger the coefficient. The coefficients rapidly become worse above 14–15 km, irrespective of averaging periods, due to the estimation error of wind velocity (Fukao et al., 1986). This result does not vary much if the arithmetic mean vertical wind velocity is estimated from radial velocities in two or three beams

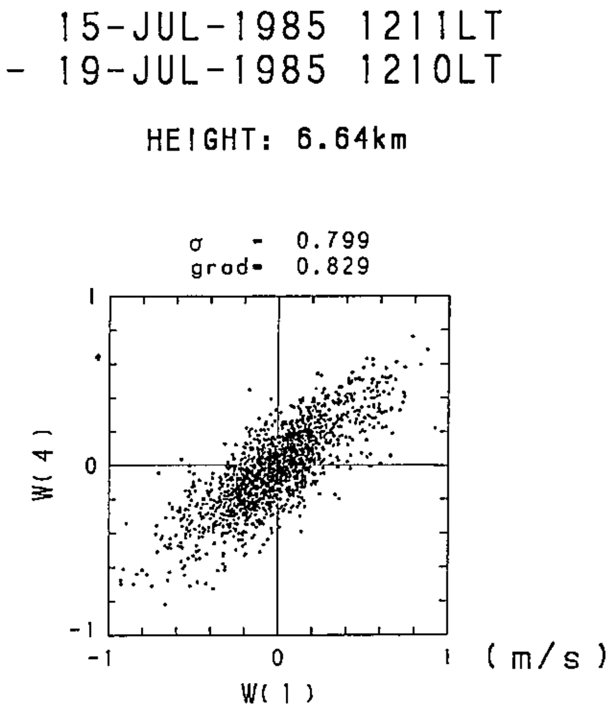

FIG. 11. Scatter diagram for the vertical wind measured directly [$w(1)$] vs measurement by the four-beam method [$w(4)$]. All reliable wind data obtained during the 4-day period of observation at a height of 6.64 km are used. Here σ is the cross-correlation coefficient, while "grad" indicates the gradient of linear regression line.

instead of four beams. It is suggested from this figure that the wind field is, on an average, uniform over the beam distance for a period range longer than ~30 min. However, wind fluctuations with periods shorter than ~30 min will probably lead to erroneous velocity estimates for MST radar observations. The short-period wind fluctuations obtained by beam steering technique should be treated with great care.

A gradient in the horizontal wind field may cause an erroneous calculation of the vertical wind for the four-beam method, but the effect is probably not large with the small beam separation used in the present observation (Reid, 1987).

5. Concluding remarks

Utilizing the fast beam steerability of the MU radar, determination of momentum flux is compared between the three- and four-beam methods. A systematic difference appears between the two methods due primarily to the spatial variation of wind in horizontal scales less than the distance between the beams. This suggests that short-period wind fluctuations estimated with the beam steering technique of MST radars will not always be real but sometimes erroneous. The momentum fluxes measured by the two methods are almost the same for wind fluctuations in a fairly long-period range, e.g., longer than 6 h. The short-period wind fluctuation produces a considerably large "noise" flux when measured by the three-beam method.

It is concluded that the momentum flux should be measured by the four-beam method but that the three-beam method can be used in the lower stratosphere and upper troposphere region where the vertical flux of horizontal momentum is generated primarily by the longer-period fluctuations. In this height range, the longer-period momentum flux is due primarily to synoptic-scale or mesoscale disturbances, while the shorter-period flux is due primarily to intense vertical air motion. The short-period momentum flux cannot be measured precisely by the three-beam method. In this study, performed during a 4-day period in summer at 35°N latitude, the contribution of traveling gravity waves to the momentum flux was unimportant in this region compared to the mesospheric height.

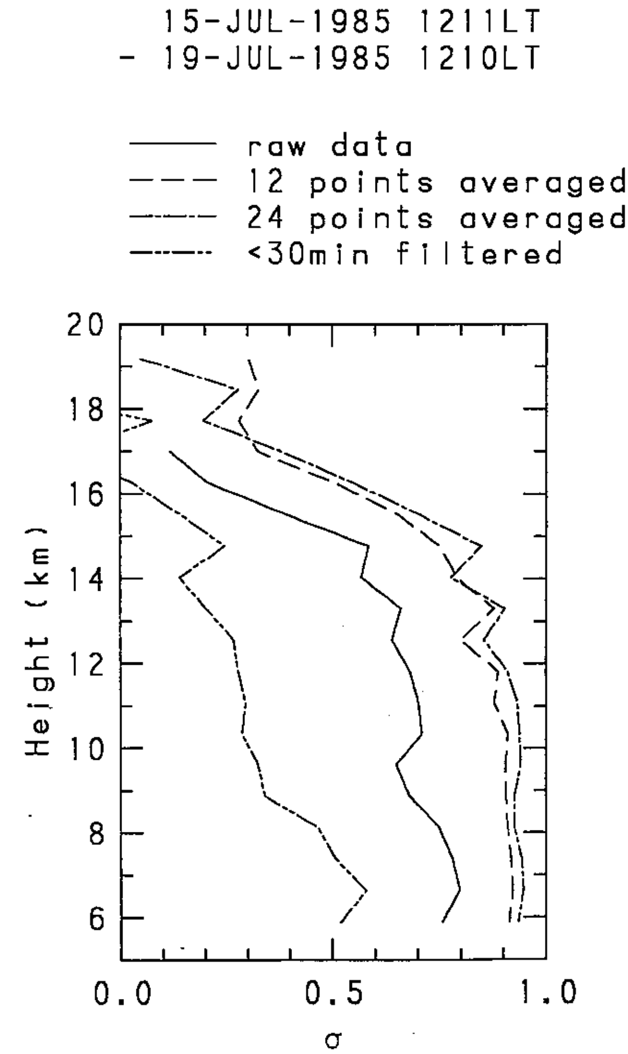

FIG. 12. Four-day average of the cross-correlation coefficient (σ) between $w(1)$ and $w(4)$ vs height for different period-ranges.

Further investigation will be necessary to determine the averaging period suitable for the mean value computation. Realistic wave fields often appear to consist of a superposition of many waves of various characteristics, with quasi-random periods of less than a few hours (Vincent and Reid, 1983). Therefore, the possibility that 4 days may not be suitable as the period of averaging to determine the proper mean value will not be denied in the present observation. Presumably, a longer period will be needed, and an analysis of longer period observations based on the four-beam method will be made in the future.

It can also be said that it is not a monochromatic wave, but various kinds of waves with different phase velocities that constitute the momentum flux, making the observed values diverse. We need to investigate the wave parameters that contribute to the momentum flux in order to determine the suitable period for averaging.

We are inclined not to extend physical interpretations of the time mean momentum flux observed from a single station beyond noting that the VHF Doppler radar technique is expected to provide new information concerned with the momentum fluxes in the lower atmosphere which may not necessarily be the same as that obtained on a synoptic scale by conventional meteorological instruments (e.g., Kung, 1966).

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