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VHF Radar Measurements of Small-Scale and Meso-Scale Dynamical Processes in the Middle Atmosphere [and Discussion]

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VHF radar measurements of small-scale and meso-scale dynamical processes in the middle atmosphere

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The principle of VHF radar observations of the atmosphere is briefly summarized. Gravity-wave and turbulence sources, as seen by VHF radar, are described, followed by an outline of observations of upward-propagating gravity waves and the corresponding transport of energy and momentum. Frequency and wavenumber spectra are discussed in terms of a universal spectrum of waves and quasi-two-dimensional turbulence. The divergence of vertical flux of horizontal momentum, which indicates the interaction of waves with the mean wind, is considered. Saturation of gravity waves often occurs in the middle atmosphere where it can cause turbulence. This controls the vertical transport of passive tracers by means of turbulent diffusion. These phenomena are investigated by VHF radars, particularly in the mesosphere. The phenomenology of 'turbulence echoes' from the mesosphere, influenced considerably by the electron density profile, is examined. The generation mechanisms of turbulence and its coexistence with stable stratifications are explored. The presented model offers an explanation of the different features of the observed radar echoes and provides a better understanding of the interaction of meso-scale and small-scale phenomena of waves and turbulence in the middle atmosphere. Finally, a summary of some remaining questions that could be solved by further collaborative efforts, including the application of radars, is given.

1. Introduction

During the Middle Atmosphere Programme (MAP), a new radar technique has been developed and reached a remarkable state of the art to investigate the structure and dynamics of the middle atmosphere. The radars have become known as MST radars, because they are very effective instruments for studying the mesosphere, the stratosphere and the troposphere (see, for example Balsley & Gage 1980). They are also called VHF radars, because the most common radar wavelength used is about 6 m, which is in the lower portion of the VHF band of the radio-wave spectrum. Because of their good resolution in time (some 10 s) and in altitude (some 100 m), they constitute very appropriate tools to study small-scale and meso-scale phenomena in the middle atmosphere, such as waves and turbulence. The investigation of these processes is of basic interest in understanding the dynamics of the atmosphere. Because waves and turbulence have relevant effects on the large-scale circulation of the middle atmosphere, their observations and detailed investigations have also attracted major interest in theoretical and modelling studies (Fritts *et al.* 1984).

Quite a few review papers have been published on the VHF radar technique as well as on the achieved results of the investigations of the middle atmosphere (Gage & Balsley 1978, 1984; Harper & Gordon 1980; Rastogi 1981; Röttger 1984). Several workshops have been held and the proceedings were published in *Handbook for MAP* (Bowhill & Edwards 1983, 1984, 1986).

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Operations of these radars were also essential in several MAP programs, such as ATMAP, GRATMAP, MSTRAC and WINE. VHF radars obviously form part of future projects during the continuation of MAP, the Middle Atmosphere Cooperation (MAC), and are becoming more frequently used in routine operations to study and forecast meteorological processes in the middle and lower atmosphere. Radars operating at other frequencies, such as in the high MF band, are also employed to study particularly winds and waves in the mesosphere but are not subjects of this paper. Also meteor radars, incoherent scatter radars and the LF drift technique, which are used to investigate the dynamics of the upper mesosphere and lower thermosphere (Rüster 1984; review papers cited in Vincent 1984) are not treated here.

This paper deals particularly with the MST–VHF radar observations of 'small-scale and meso-scale phenomena'. This term includes gravity waves and turbulence, i.e. those phenomena with timescales of the order of a day and less, horizontal scales of some 1000 km down to a few hundred metres, and corresponding vertical scales that are about 2–3 orders of magnitude smaller than the horizontal scales.

Space limitations do not permit a complete review of small-scale and meso-scale processes observed by VHF radars. Thus, the purpose of this paper can only be to outline a few highlights that appear intriguing and yet unresolved to the author. A brief summary of the technique and observational results has to be given, however, because this will help to understand the open questions and the possible answers or explanations.

2. Radar investigations of the atmosphere

More than a decade ago, Woodman & Guillen (1974) at the Jicamarca Radar Observatory developed the principle of the MST–VHF radar technique and recognized its great potential for remote sounding of the middle atmosphere. Although prospects that the entire altitude range from 1 to 100 km could be monitored have not been fulfilled, these radars have become invaluable tools to study turbulence, waves and winds. Woodman & Guillen were the first to report radar observations of gravity waves in the mesosphere and also showed that the VHF radar echoes are caused by scatter from turbulent fluctuations of the refractive index of the atmosphere, rather than by Thomson or incoherent scatter from free electrons. They also detected echoes from the stratosphere and were able to deduce mean vertical and horizontal velocities.

After further radars were constructed for the special purpose of studying the lower and middle atmosphere (see reviews by Gage & Balsley 1978; Röttger 1984), it was found that not only scatter from turbulent fluctuations but also partial or specular reflection from steep vertical gradients of the refractive index occurs. The reflected as well as the scattered radar echo power is produced by that component of the spatial spectrum of the variation of the refractive index whose wavelength is half the radar wavelength. To detect and interpret echoes, it is necessary that the turbulence causing the scattering is in the inertial subrange of the Kolmogoroff spectrum. For spatial scales of 3 m this is mostly justified up to mesospheric heights (Hocking 1985); gradient scales of 3 m should consequently also exist and will cause partial reflection.

The refractive-index variations, expressed by the so-called turbulence refractive-index structure constant C_n^2, are intimately related to variations of the atmospheric parameters: humidity, temperature, neutral density and electron density. The contributions due to humidity variations are dominant only in the troposphere. In the stratosphere, temperature variations are essentially contributing, and in the mesosphere, electron-density variations are responsible for the refractive index variations. Neutral density variations generally play a negligible role but indirectly contribute to the refractive index changes. Because of the high collision frequency between neutrals and ions in the partly ionized mesosphere, however, the neutral density variations due to turbulence are transformed to electron density variations. These then constitute the major contributions to the refractive index changes in this altitude region. Hocking (1987*a*) has examined in detail the radar studies of the mesosphere and also the causes, the nature and the co-existence of specular and turbulent scatterers as well as the electron-density influence.

The main parameters determined with a VHF radar are the intensity or power, the Doppler-spectrum shift and the Doppler-spectrum width of the radar echo. These are measured as functions of time, altitude and beam direction. From these measurements, the intensity, anisotropy and intermittency of turbulence, the intensity and persistency of refractive-index gradients, i.e. the atmospheric stability, and the three-dimensional bulk velocity can be deduced. Furthermore, parameters of atmospheric waves, such as wavelengths and phase speeds as well as the vertical flux of horizontal momentum, can be determined. More detailed descriptions how these parameters are measured and which suitable means have to be applied to deduce relevant conclusions can be found elsewhere (Hocking 1983, 1985, 1987*a*; Vincent & Reid 1983; Röttger 1984; Röttger & Ierkic 1985; Fukao *et al.* 1987; Reid 1986).

The quantities outlined in the latter paragraph are typically measurable with altitude resolutions of 150 m to about 1 km in the altitude range up to 20–30 km in the stratosphere, and between about 60 and 90 km in the mesosphere, depending on radar sensitivity and atmospheric conditions, namely the state of turbulence or stability, and electron density (in the mesosphere). The time resolution is adapted to the physical phenomenon of interest and can be as good as some 10 s. The most sensitive radars, namely the Jicamarca, Arecibo, Pokerflat, MU, and SOUSY-VHF radars, use antenna apertures of several tens of thousands of square metres down to a few thousand square metres. The MST radars operate in the monostatic mode with different antenna beams of 1–7° width directed close to the zenith. They use average transmitter powers of about 100 kW to several kilowatts (see Röttger (1984) for a complete list).

Observations with all these radars verified generally that the average echo intensity decreases by a factor of two for an altitude increment of 1–2 km in the stratosphere. At vertical incidence this can be consistently explained by the decrease of atmospheric density and the magnitude of the vertical-displacement spectrum with altitude and a collection of transversely coherent, horizontally stratified, stable laminae or sheets of gradients of the refractive index (Hocking & Röttger 1983; Gage *et al.* 1985). This mechanism is called 'Fresnel reflection' if one lamina dominates, and 'Fresnel scatter' if several laminae are in the radar volume. Fresnel reflection and scatter are anisotropic and may transit into isotropic scattering from turbulence at sufficiently large off-zenith angles (greater than 10°). The pronounced anisotropy and persistency of the laminae or sheets in the troposphere and stratosphere are regarded as a measure of atmospheric stability (Balsley & Gage 1980; Röttger 1980). A similar layered structure of intensity and intermittency is also observed in the mesosphere. The vertical thickness of these echo structures is often much smaller than the optimum VHF radar height resolution of some 100 m. It can be reasonably assumed that some of these structures are thinner than several tens of metres, although intense scattering layers of a few kilometres in thickness are also observed, particularly in the mesosphere. The mesospheric echo intensity is characterized by a strong

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diurnal and seasonal variation. When mesospheric echoes are observed, their intensity is generally comparable to the intensity of stratospheric echoes from 15–25 km altitude.

An example of MST radar echo structures is shown in figure 1. In the following sections we will explain such typical echo features and describe their relation to turbulence, stable stratifications and atmospheric gravity waves.

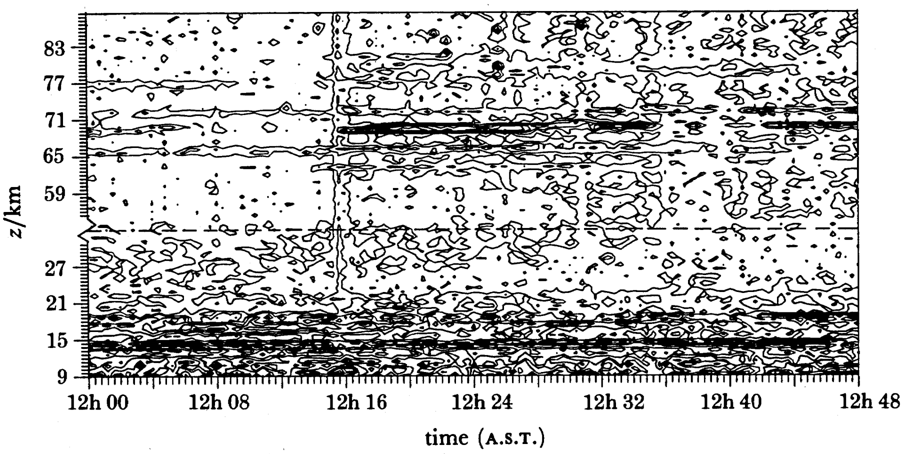

FIGURE 1. Contour plot of tropospheric, stratospheric and mesospheric VHF radar echoes measured at the Arecibo Observatory in Puerto Rico. (From Röttger *et al.* 1983.)

3. Radar investigations of gravity-wave sources

The most important natural generation mechanisms of waves in the atmosphere are probably the air flow over mountainous terrain generating mountain or lee waves, the wind shears initiating the dynamic or Kelvin–Helmholtz instability and the corresponding wave oscillations, as well as convection originating from the convective or Rayleigh–Taylor instability (see, for example, Fritts & Rastogi 1985). The latter can cause convective plumes penetrating upwards into stably stratified regions where buoyancy waves are generated. These waves generated by different processes frequently break into turbulence, but they can also propagate away from their source region, which is mostly in the troposphere and lower stratosphere. Of particular interest is the upward propagation of such waves, whereby energy and momentum can be transported into upper atmospheric regions.

Lee waves have occasionally been observed by VHF radars (Röttger *et al.* 1981; Rüster & Klostermeyer 1983). Indirect indications that lee waves generate substantial amounts of turbulence in the stratosphere have been reported by Nastrom *et al.* (1985). There is no evidence to date that these waves have been detected in the mesosphere, although it has been suggested that a higher amount of turbulence in the middle atmosphere should exist in orographically predestined regions.

Quite a few very detailed case studies of Kelvin–Helmholtz instability-generated waves have been performed, showing that the radar observations are consistent with theoretical modelling (Rüster & Klostermeyer 1983). However, direct evidence from radar observations of waves propagating away from the source region is rare.

Strong wind-shear regions occur in jet streams, of which an example (measured with the SOUSY–VHF radar in W. Germany) is displayed in the velocity contour plot of figure 2*a*. The region of largest horizontal wind is stippled. The strongest vertical shear of horizontal wind is observed in the altitudes below and above the wind maximum. This shear region is dynamically unstable, as illustrated in figure 2*b*. The vertical velocities show large fluctuations with amplitudes up to 1 m s^{-1} and with a period of about 8–10 min, which is close to the local Brunt–Väisälä period. It is quite clear from the radar measurements that these oscillations are confined to only the critical shear regions. This evidence is also demonstrated by the examples discussed by Rüster & Klostermeyer (1983). There are apparently no waves of the observed periods propagating vertically away from the wind-shear source region. However, there are many other radar observations that show the existence of gravity waves in the stratosphere and the mesosphere. It is argued that these often originate from tropospheric shear regions. It is, thus, evident that further radar investigations of source, radiation and propagation of gravity waves generated in shear regions still appear to be needed (M. E. McIntyre, personal communication 1986).

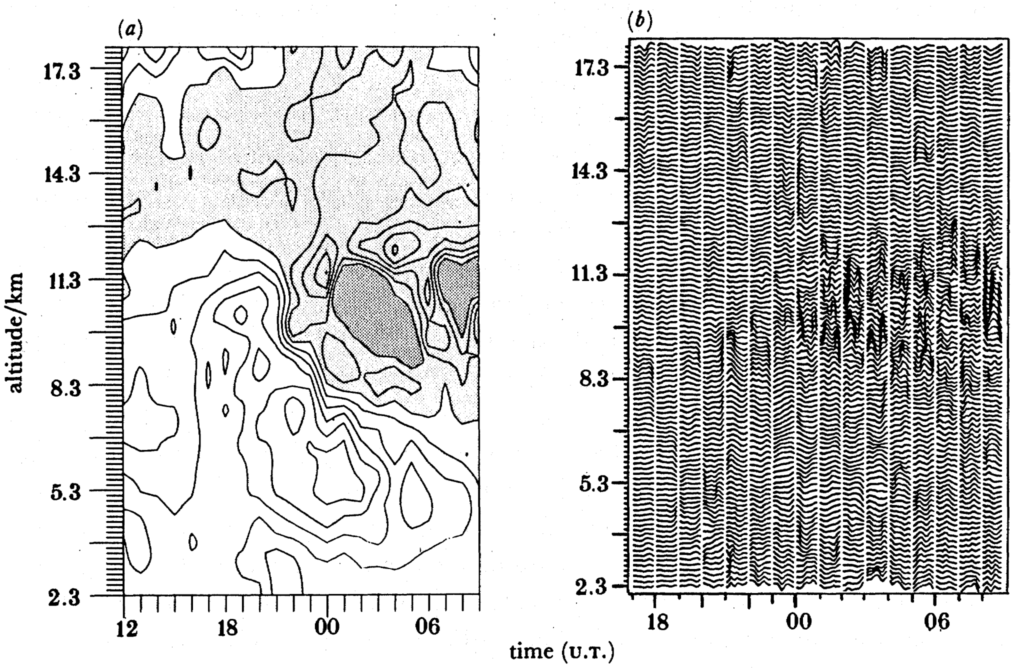

FIGURE 2. Contour plot of wind speed (*a*) showing a high-speed jet core (densely stippled region) and vertical shears below and above it. In these shear regions dynamical instability occurs, as illustrated by the vertical velocity fluctuations in (*b*). Note that (*b*) shows time intervals of 12 min at every full hour. (After Röttger & Schmidt 1981, Larsen & Röttger 1982.)

Other wave sources are velocity fluctuations near an interface between a turbulent region and a stably stratified layer. This is a particularly efficient source mechanism of middle-atmospheric waves when cumulonimbus towers of thunderstorms reach the upper troposphere and eventually penetrate into the stable lower stratosphere. Röttger (1980) has reported a spectrum of oscillations in the stratosphere with maximum vertical velocity at, and a steep cut-off above, the local Brunt–Väisälä frequency, which was observed after a thunderstorm had penetrated up to the tropopause. S. A. Bowhill & S. Gnanalingam (personal communication 1985) reported enhanced wave activity in the middle atmosphere during times of high cloudtop altitudes, and even travelling ionospheric disturbances were reported to be related to penetrative convection (see Röttger 1980). There is, thus, some observational evidence that gravity waves generated by penetrative convection are present in the middle atmosphere.

4. Spectra of velocity fluctuations and gravity waves: two-dimensional turbulence

The spectra of vertical velocity fluctuations have a very peculiar shape. This shape appears to be quite consistent throughout the troposphere up to the thermosphere (figure 3). VanZandt (1982) has suggested that these kinds of universal spectra are given by a random field of gravity waves, analogous to the Garrett–Munk displacement spectra caused by cascading of internal waves in the ocean. It is quite evident from Röttger & Ierkic's (1985) investigations that the power density near the Brunt–Väisälä frequency is caused by atmospheric gravity waves. Also, computations by Scheffler & Liu (1985), based on the assumption of the gravity wave model, yield the universal spectrum shape. Doppler shift of waves in a mean background wind, which was considered by C. H. Liu & A. O. Scheffler (personal communication 1986), does spread the power density to higher and lower frequencies. This may be the reason why different spectral shapes are observed during periods of high wind velocity, as compared with those spectra in figure 3, obtained during quiet wind periods. Other effects, namely the spillover from horizontal wind fluctuations during lee-wave conditions or because of broad vertical antenna beam widths, could also explain these observations. The spectra of Röttger (1981) reveal the spillover to higher frequencies in the lower stratosphere, but still indicate the peak near the Brunt–Väisälä frequency. It is therefore suggested that the profile of the Brunt–Väisälä frequency can be determined from the vertical velocity spectra, provided that the atmosphere is stably stratified and the winds are low to moderate.

The spectra of horizontal velocity fluctuations were also studied in detail. There are some difficulties, however, because VHF radar-beam positions are fairly close to the zenith, such that the measured components of horizontal and vertical velocity cannot easily be separated. Scheffler & Liu (1985) have modelled this effect and discussed the limits of applicable wave frequencies and beam directions. Observations of mesospheric velocity fluctuations reveal power spectra with fairly uniform slopes close to $-\frac{5}{3}$ (Balsley & Carter 1982). However, stratospheric spectral slopes deduced by other authors (Röttger 1981; Rastogi & Bemra, personal communication 1986) differ quite a bit from the $-\frac{5}{3}$ slope. Gage & Nastrom (1985) have converted vertical velocity spectra to the corresponding horizontal velocity spectra by using the gravity-wave dispersion relation. They found that the power density of these converted spectra is an order of magnitude smaller than the observed power density. They concluded that this inconsistency points to the existence of quasi-two-dimensional turbulence, which dominates the horizontal fluctuations. They supported their conclusion by showing a reasonable accord between horizontal wavenumber spectra, measured by aircraft, and Taylor-transformed frequency spectra, measured by VHF radar. Gage & Nastrom (1985) therefore claim the co-existence of two-dimensional (quasi-horizontal) turbulence with a nearly universal spectrum of gravity waves.

Smith *et al.* (1985, 1986) concluded, however, that their mesospheric observations are consistent with the model that gravity waves are the dominant motion, but Larsen *et al.* (1985) found that their observed frequency spectra and vertical wavenumber spectra of vertical

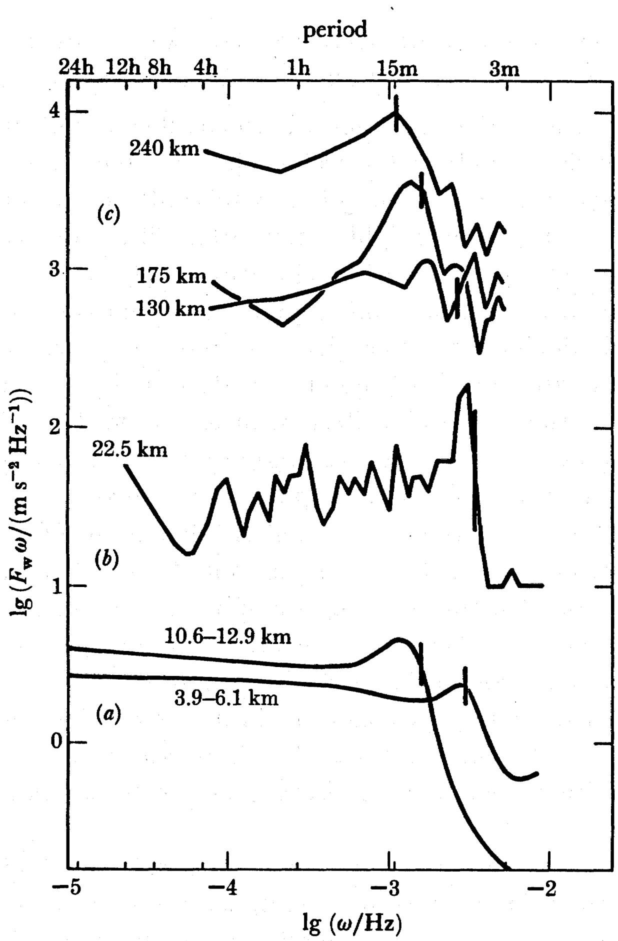

FIGURE 3. Frequency spectra of vertical velocity for tropospheric (*a*), stratospheric (*b*) and thermospheric (*c*) heights. (After VanZandt 1985.)

velocities in the stratosphere do not support the universal gravity-wave prediction. They refer to the fact that a quasi-geostrophic flow behaves like two-dimensional turbulence and that this would be consistent with a cascade of energy from small to large scales, contrary to the commonly known cascade of energy from large to small scales in the three-dimensional inertial subrange.

More light could be shed on this controversy by concentrating to a greater extent on the wavenumber spectra. A few such spectra have been measured, but indicate quite differing slopes. Attempts have been undertaken to deduce also the wavenumber–frequency spectra, which seem to indicate features of propagating gravity waves. However, the intermittency of radar echoes and their limited vertical extent have not yet led to definitive results.

Conclusive evidence is therefore still needed to resolve the apparent controversial issue of gravity waves and two-dimensional turbulence in the middle atmosphere, although one may be inclined to believe in their coexistence. E. M. Dewan (personal communication 1985) has suggested further experimental tests to distinguish waves from two-dimensional turbulence, based on the fact that waves are coherent and propagate, while turbulence is incoherent and does not propagate, but rather is advected.

5. Vertical transport of kinetic energy and momentum, wave mean-flow interactions, wave saturation and turbulence

Although many authors assume that the observed velocity fluctuations are caused by gravity waves, it is found at many places (Balsley & Garello 1985) that the variation of kinetic energy with altitude does not readily fit this assumption. VanZandt (1985) states that there is a considerable loss of wave energy at all heights above 10 km if the observed fluctuations are indeed entirely caused by gravity waves. Although Fritts (1984) and others claim that saturation is mainly due to wave breaking, other processes should be included, such as the influences on wave propagation of vertical gradients of wind and/or temperature, wave–wave interaction, viscous and radiative damping, nonlinear effects and parametric instabilities. To determine the relative importance of these effects with respect to dynamical and convective instabilities, conclusive data on temperature and wind profiles as well as complete information on gravity-wave parameters in the middle atmosphere are needed.

Propagating gravity waves transport energy as well as momentum. The considerations in the preceding section lead to the conclusion that a substantial part of the energy of vertically propagating waves is deposited in the middle atmosphere. The vertical flux of horizontal momentum by gravity waves is also of considerable interest, because its divergence due to wave dissipation results in an acceleration of the mean flow towards the phase speed of the waves. Such accelerations are needed to damp the mean zonal winds to satisfy the heat and momentum budgets in the mesosphere (Holton & Zhu 1984). In addition to the Reynolds stress associated with the waves, other mean forces, such as viscosity etc., can also play a role (McIntyre 1980).

Vincent & Reid (1983) were the first to develop a new radar method by using coplanar antenna beams with an MF radar to measure mesospheric gravity-wave momentum fluxes. They showed that gravity waves provide a significant acceleration of 20 m s^{-1} d^{-1} in the mesosphere, which compared reasonably well with the wave drag required to balance theoretical estimates of the zonal winds. They found that most of the wave drag is caused by absorption of waves with periods less than one hour. Fritts (1984) has suggested, based on theoretical considerations, that the transport of momentum could be accomplished primarily by relatively high-frequency waves. Reid (1986) has stressed the importance of the short-period motions and additionally pointed out their directional dependence and seasonal variations. He has also given proof that the zonal mean-flow acceleration associated with saturated gravity waves is generally in the correct sense and of the right magnitude to satisfy the momentum balance in the mesosphere.

There are also attempts underway to measure the momentum flux due to gravity waves and even synoptic-scale waves in the troposphere and stratosphere. This is of particular importance because the numerical weather-prediction models also need a frictional force to yield a realistic magnitude of the mean zonal wind (T. N. Palmer, personal communication 1985). Wave mean-flow interactions could be deduced from the observation that the short-term (less than 1 hour) velocity variability due to gravity waves in the lower stratosphere was correlated with long-term wind variations due to synoptic-scale disturbances (Röttger 1981). Also Nastrom *et al.* (1985) concluded from the diurnal variation of the turbulence refractive-index structure constant that gravity waves deposit a portion of their momentum in the stratosphere.

6. Features of turbulence echoes and the effects of the background refractive-index profile

It has been accepted that turbulence in the mesosphere arises from the unstable breakdown of tides and gravity waves (Lindzen 1981). The generated turbulence would prevent the further growth of wave amplitude with height. This saturation is regarded to be through the convective instability of short period waves (Fritts 1984), dissipating excess wave energy before dynamical instability can occur. The seasonal variation of mesospheric VHF radar echoes appears to be a clear indication for this effect. Balsley *et al.* (1983) have evaluated the observations over a couple of years of the Poker Flat VHF radar in Alaska. They reported about a period of three months around the summer solstice during which an intense and nearly continuous echo layer of 4 km thickness was observed near 86 km. During the remainder of the year, particularly in winter, the echoes were much weaker, more sporadic, and occurred at an altitude between 60 and 80 km. There was also a very abrupt transition to and from the summer conditions.

The results of Balsley *et al.* (1983) were largely confirmed by observations in northern Norway (Czechowsky & Rüster 1985), but the altitude coverage of the echoes was somewhat more extended here and the winter echoes were observed in structured layers. The winter echoes at both locations, Alaska and Norway, were also characterized by clear diurnal variations with maxima around noon and sporadic echoes during the night-time hours. The diurnal variation during winter and summer evidently reflects the normal diurnal variation of D-region electron density. At both locations, a correlation between riometer measurements (indicator of D-region electron density) and echo occurrence as well as distinct echo features, such as layer thickness, was observed. It was assumed by Balsley *et al.* (1983) that the summer echoes are primarily resulting from shear-instability of a low frequency tidal motion in the region of the highly stable arctic summer mesopause. The winter echoes were supposed to arise from the nonlinear breakup of upward-propagating gravity waves. This is consistent with Lindzen's (1981) theory. However, other mechanisms, such as wave-amplitude growth in regions of large static stability (T. E. VanZandt, personal communication 1987) or the extension of the inertial subrange in the electron gas of the mesopause region by the presence of heavy positive cluster ions (M. C. Kelley, personal communication 1987) could also account for the intense summer mesosphere echoes.

Balsley *et al.* (1983) have briefly discussed the limitations of their conclusions because of missing information on the electron-density profile that crucially determines the mesospheric echo intensity (Hocking 1985). This dependence is illustrated in figure 1. The sudden commencement of echo power and detectability of mesospheric layers at 1215 A.S.T. (Atlantic Standard Time) was related to an electron density enhancement due to a solar flare effect (demonstrated by simultaneous measurements by incoherent scatter radar). If simultaneous observations of the D-region electron density profile are not included, a completely misleading picture of mesospheric turbulence could evolve. This has to be taken into account particularly in the high-latitude auroral regions where particle precipitation from the magnetosphere can substantially and very suddenly enhance the D-region electron density.

We have to note here that observations of tropospheric and stratospheric echo structures could also be misinterpreted in terms of turbulence, particularly because of the structure of humidity in the troposphere (Nastrom *et al.* 1985) and of temperature in the stratosphere. The latter has an influence on stability that reflects itself in the intensity, angular anisotropy and persistency of the partially reflected echoes observed with vertically beaming VHF radars. The deduction of the turbulence refractive-index structure constant C_n^2 from echo intensity therefore should be done with care (Hocking 1983, 1985).

7. Localized turbulence, gravity-wave climatology, and turbulent diffusion

Royrvik & Smith (1984) and Smith *et al.* (1986) have compared rocket measurements of electron density and temperature with simultaneous VHF radar measurements of the mesosphere. The former have found that the radar echo intensity is consistent with the rocket measurements of electron-density fluctuations, and the latter have shown that the regions of greatest echo intensity coincide with the locations of most unstable temperature-lapse rate and of the maximum wave-velocity perturbation. Smith *et al.* (1986) conclude that the regions of intense turbulent mixing of the electron-density gradient are closely coupled to the saturation of large-scale inertia gravity waves. The occurrence of convective instability in regions of superadiabatic-lapse rate is consistent with the theoretical arguments of Fritts (1984) and Fritts & Rastogi (1985). However, this is not consistent with the findings of Rüster (1984) and Czechowsky & Rüster (1985) that echo power maxima may be associated with instabilities generated in the maximum shear regions of gravity waves. All these investigations have concentrated on echo intensity, which is not an appropriate indicator of mesospheric turbulence and could yield far too large turbulence energy dissipation rates. Studies of spectral width could be more useful, because it is a more direct indicator of the turbulence energy dissipation, provided that beam-broadening and shear-broadening effects etc. are considered (Hocking 1985).

Our considerations indicate that the interpretation of radar echo intensity has to be made with quite some care, particularly for mesospheric observations. A reasonably useful information base, which constitutes a necessary input for global circulation models of the middle atmosphere, results from the climatology of gravity waves (and turbulence) rather than from MST radar echo features. In particular, the variance of horizontal and vertical velocity fluctuations and the divergence of vertical flux of horizontal momentum deduced from Reynolds stress profiles, filtered for specific spectral portions, are needed on a long term and global base. In figure 4, an example of the seasonal variation of velocity fluctuations measured with the Poker Flat VHF radar is shown. A similar variation was also found at mid-latitudes with the Saskatoon MF radar (A. H. Manson, personal communication 1987). Although one cannot directly deduce turbulence intensity from the velocity variance, unless one knows the temperature and mean wind profiles, such a seasonal analysis may be regarded very useful. We note that the seasonal variation of echo intensity (Balsley *et al.* 1983) is substantially different from that of the velocity fluctuations in the mesosphere and no clear relation between the fluctuations in the troposphere, stratosphere and mesosphere is seen. A comparison of these observational results with the model of Lindzen (1981) on the generation and filtering of upward-propagating gravity waves deserves some attention.

There is apparently no doubt that turbulence is generated by gravity waves and tides. Turbulence in turn is dissipated into heat and it causes diffusion of heat, momentum and matter. These phenomena can be quantified by the turbulence energy dissipation rate and the turbulence or eddy diffusion coefficient. The breaking of gravity waves into turbulence imposes

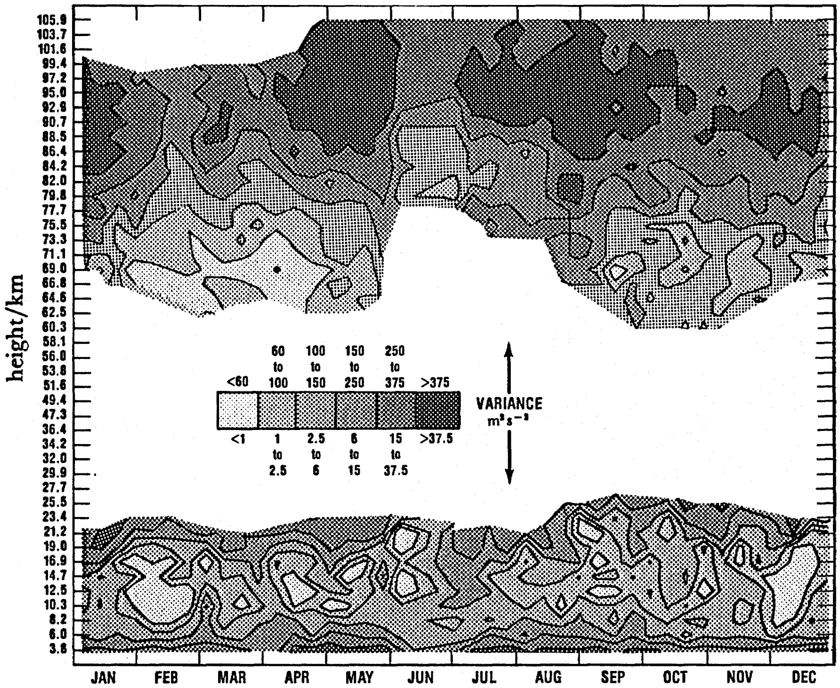

FIGURE 4. Seasonal variation of the variance of wind fluctuations measured at high latitudes. (From Balsley & Garello 1986.)

an important influence on the dynamics (Lindzen 1981) as well as on the chemical composition of the mesosphere and the lower thermosphere (Garcia and Solomon 1985). We will only briefly mention turbulent diffusion measured by VHF radar in the mesosphere because more details can be found elsewhere (see, for example, Hocking 1983, 1985, 1987*a*). The eddy diffusion coefficient within turbulent layers can be deduced from the measured Brunt–Väisälä frequency and the mean square fluctuating velocity amplitudes. As shown in a case study by Röttger (1987*a*), it is as small as 20–50 $m^2 s^{-1}$ and decreases with altitude in contrast to median profiles collected by Hocking (1987*b*), but in accordance with recent *in situ* observations of Thrane *et al.* (1985).

8. Origin of radar-detected turbulence and laminae

It is unquestionable from many experiments that turbulence structures are intermittent in time and space, as demonstrated by figure 1. A clear feature is the splitting into several, often periodically arranged layers or laminae. Although the intensity of these structures can vary intermittently, they can recur persistently at the same altitude over longer time periods, or frequently move downward (Rüster 1984; Smith *et al.* 1986).

Apparently, an explanation that such structures as shown in figure 1 are generated by short-period gravity waves does not apply, as figure 5 indicates (from Röttger 1987*b*). We notice quite a substantial wave activity at many different periods from about 4 min upwards. If wave breaking occurred, we should see an increase of intensity and spectrum width at certain phases of these oscillations. Such intensity bursts occur only very rarely (around 14h00 A.S.T. at 75.6 km, or after 15h00 A.S.T. at 76.8 km). When carefully viewing the records, we often find

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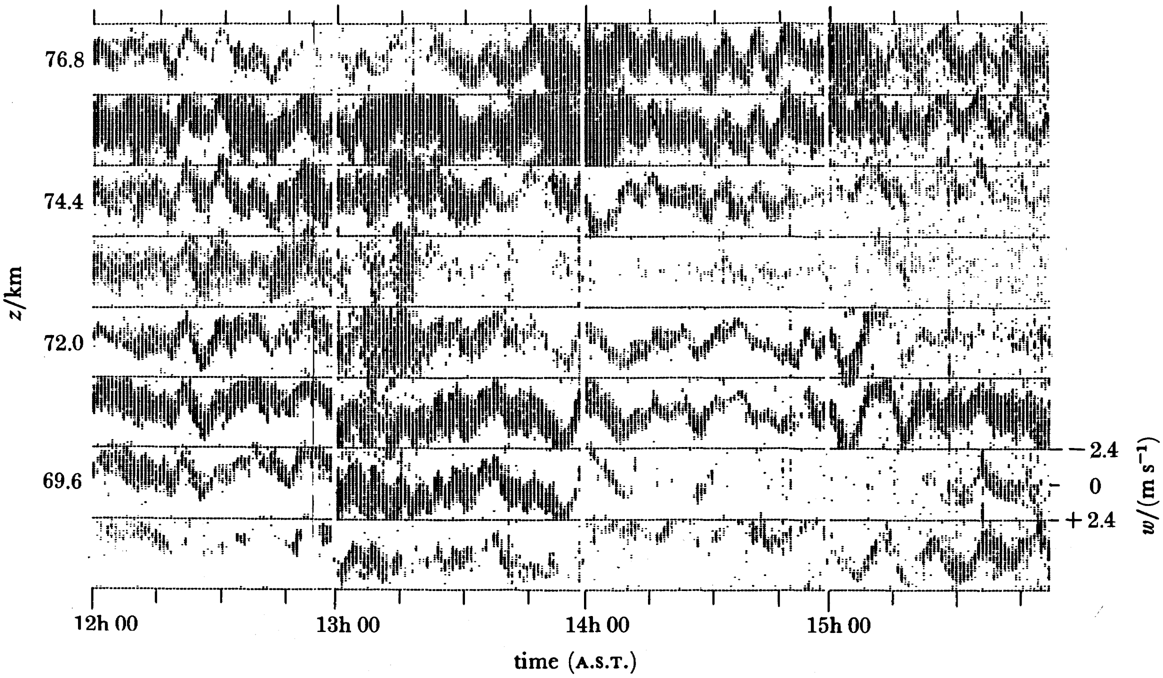


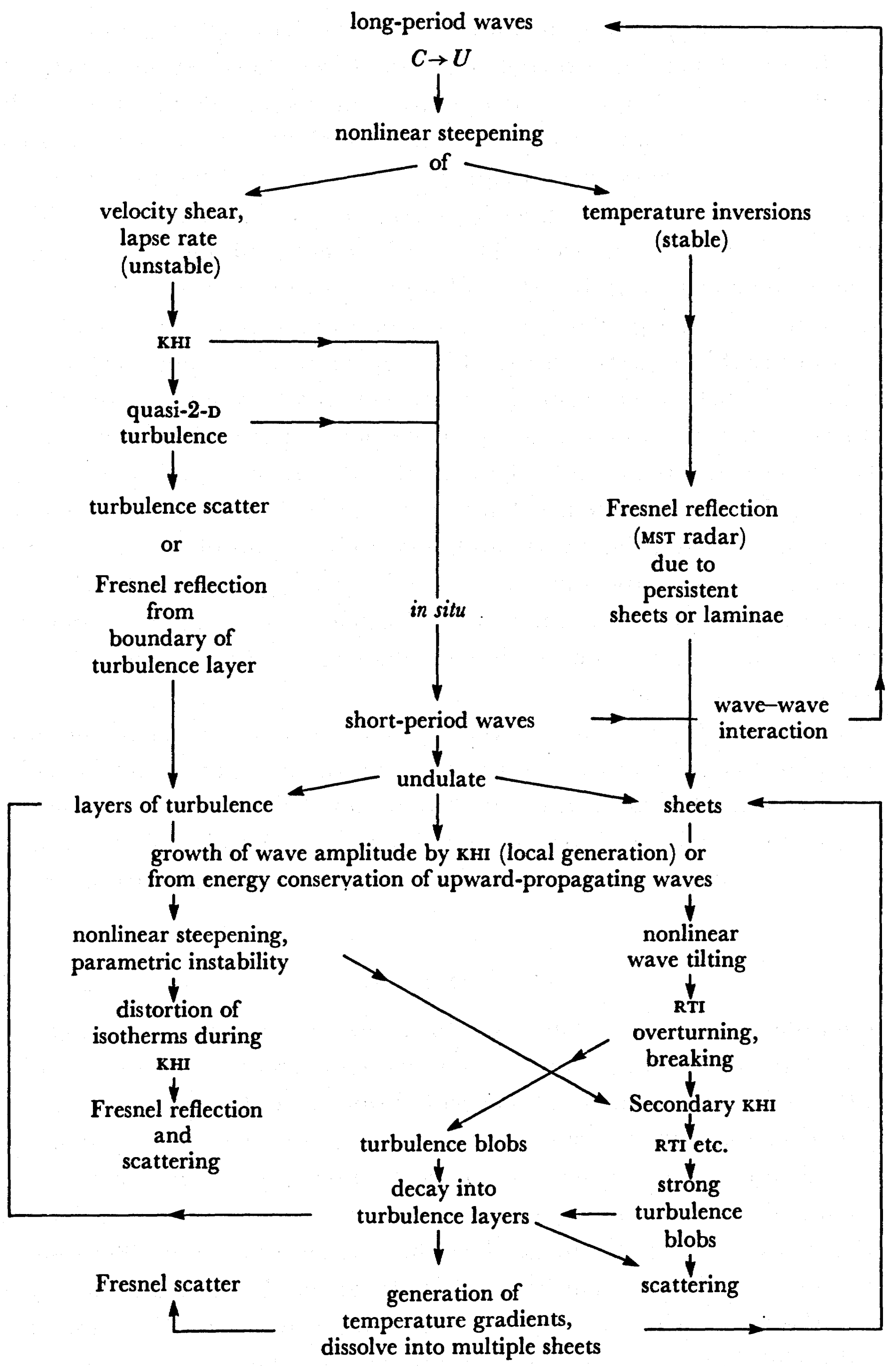
FIGURE 5. Dynamical spectra of mesospheric echoes, measured at quasi-vertical incidence at low latitudes in Arecibo, Puerto Rico. (From Röttger 1987*b*.)

non-sinusoidal velocity variations. This indicates a nonlinear steepening effect (Mobbs 1985; Weinstock 1985) that transfers energy from the fundamental into harmonics without breaking. Another peculiar effect is also seen when a high-frequency wave is superimposed on a low-frequency wave (at 69.6 km after 13 A.S.T.). This points to wave–wave interaction or parametric instabilities.

Because there is no distinct amplitude growth with height of these wave oscillations, a saturation process has to be invoked if we do not accept that these waves are locally generated or guided in vertically narrow ducts. Because we seldom see a clear indication of wave breaking into turbulence, we could also assume other dissipation effects, such as energy transfer into higher harmonics (nonlinear steepening), parametric instabilities, radiative or viscous damping and heat conduction.

There is evidently no proof that the mesospheric echo structures are generated by the simultaneously existing short-period gravity waves. More likely generation mechanisms are lateral convection, quasi-geostrophic flow at meso-scales, or vortical modes as seen in the ocean. There is some indication of a connection of the sheets or laminae and very-long-period inertia gravity waves. The longer the period, the shorter is the vertical wavelength of gravity waves, and the possibility for increased shear and temperature changes (and its steepening) becomes quite pronounced. More arguments to support the assumption that inertia gravity waves play a considerable role are found in Röttger (1987*b*). It is apparent that such long-period waves are existent in the stratosphere (Maekawa *et al.* 1984) as well as in the mesosphere (Yamamoto *et al.* 1987). Also Mobbs (1985) has concluded that wave-mean flow interactions result in the formation of waves with very low intrinsic frequency. Wave steepening can take place; this generates steep quasi-vertical temperature gradients and wind shears. These lead to vertically periodic structures of stable laminae (refractive-index gradients) and/or turbulence.

We can explain the structures detected by VHF radars in the middle and lower atmosphere as a result of a wide range of waves (Röttger 1987*b*). This model is presented in scheme 1.



SCHEME 1. The interrelation of waves and turbulence as seen by VHF radar.

Long-period waves can undergo nonlinear steepening or tilting when their phase velocity C approaches the wind velocity U. Through the approach of a superadiabatic lapse rate and velocity shear, Kelvin–Helmholtz instability (KHI) is activated and quasi-two-dimensional turbulence is generated. Turbulence scatter or Fresnel reflection from the boundaries of the turbulence layers can occur. Also steep temperature inversions (stable sheets or laminae) could be caused by the steepened waves, and these inversions could be shown by Fresnel reflection.

Short-period waves, propagating upwards from lower-atmospheric sources or generated *in situ* by KHI or by two-dimensional turbulence arising from long-period waves, undulate these layers of turbulence or the laminae of temperature inversions. Besides transferring energy to long-period wave modes by wave–wave interaction (B. Dong & K. C. Yeh, personal communication 1987) these short-period waves can grow in amplitude by KHI (local generation) or because of energy conservation of upward propagating waves. Nonlinear tilting, steepening and/or parametric instability can occur. The development of tilting can be observed by Fresnel reflection due to the concurrent distortion of isotherms during KHI.

Nonlinear tilting of short-period waves can cause overturning and breaking through the Rayleigh–Taylor instability (RTI). Because this happens at certain phases of the wave, localized regions of small-scale turbulence occur. These are seen by VHF radars as blobs (Röttger & Ierkic 1985) or bursts, which are propagating with the phase speed of the wave (Klostermeyer & Rüster 1984). Blobs can spread into wider spatial scales by multiple repetition of KHI–RTI and cause thick layers of strong turbulence. Through the turbulence layers corrugated temperature gradients are generated, and the layers can break up into multiple sheets or laminae that can be regarded as remnants of active turbulence. Again waves, generated elsewhere, can undulate these turbulence layers and the laminae. We, thus, close the dynamical circle to explain the frequent simultaneous observations of independent, individual small-scale and meso-scale gravity waves and turbulence.

The described interrelation of a variety of dynamical phenomena in the atmosphere can explain the earlier recognized characteristics of VHF radar echoes, namely blobs, sheets and layers (Röttger 1980). They are consistent with accepted theories and observations of gravity waves and instabilities (Fritts & Rastogi 1985; Mobbs 1985) and they also support the notion of Gage & Nastrom (1985) of the co-existence of gravity waves and turbulence in the middle atmosphere.

9. Conclusion

The combination of radar observations with theory and models has obviously resulted in a much better understanding of the features seen by the radars and the corresponding dynamical processes in the middle atmosphere. It is accepted that it would have been impossible without the development of the VHF–MST radar technique to study meso-scale and small-scale phenomena in such detail as done in the last decade. We have to admit, however, that there is a distinct diurnal and seasonal variation of mesospheric echoes and a gap region between about 30 and 60 km that cannot yet be accessed by the existing VHF radars. Because there are firm attempts in the international scientific community to build a new and very powerful radar observatory at the Equator (S. Kato, personal communications 1986) we may hope to fill this gap region, although just marginally. Also additional instruments, such as MF–HF radar systems and lidars would be valuable to achieve more continuous data sets in time and altitude or to measure, for instance, temperature profiles in the middle atmosphere. A super-power radar could also allow us to determine whether there is a permanent background of weak turbulence in the mesosphere.

We need a further understanding of gravity-wave sources, particularly how the waves, which are generated by instabilities, propagate away from the sources and how they suffer attenuation, reflection, overreflection, steepening, tilting, overturning, breaking and (nonlinearly) interact with other waves, small-scale turbulence and the mean wind. There are further open questions arising as a consequence. Why is the energy density of mesospheric velocity fluctuations substantially smaller than expected from extrapolations of stratospheric observations? Is this explainable by a coexistence of gravity waves and turbulence? Can it also be that all small-scale mesospheric waves propagate upwards from below, or can they be locally generated? Is the breaking of waves into turbulence the only saturation mechanism, and what is the relative importance of other processes such as radiative and viscous damping, nonlinearities and parametric instabilities? Why are the frequency and wavenumber spectra of velocity fluctuations so variable? Do gravity waves and quasi-two-dimensional turbulence coexist, how are they interrelated, and what is their relative importance. What is the seasonal and global climatology of waves and turbulence? In particular, the global climatology of the vertical flux of horizontal momentum (zonally as well as meridionally) is urgently needed, for the mesosphere as well as the stratosphere. Which are the gravity-wave scales and frequencies that contribute most to energy and momentum transport? What are the essential mechanisms for generating small-scale turbulence and laminae, what is the relative importance of dynamical and convective instability, and how frequently are waves just steepened rather than overturning and breaking into turbulence? Are some of the observed structures, such as laminae, remnants of active turbulence?

The deduction of the turbulence diffusion coefficient and the turbulence energy dissipation rate from radar measurements is regarded as essential, as well as its comparison with measurements by other techniques and existing models. One may also ask how the turbulent transport competes with the transport by means of the mean vertical motion through (breaking) planetary waves and the mean global circulation. There are other questions, too. What is the frequency dependence of the MST radar echoes? How seriously is the interpretation of mesospheric VHF radar echoes distorted by the presence of positive or negative ions and by changes in the electron-density profile? How important is the influence of processes in the ionized mesosphere on processes in the neutral mesosphere, and vice versa? This question is of particular interest in polar regions because of Joule heating, particle precipitation and the existence of heavy cluster ions. Changes of composition can occur locally or by vertical transport from the lower thermosphere. This implies a need to include incoherent scatter radars to study the lower-thermosphere – middle-atmosphere coupling.

In spite of the fact that VHF–MST radars have already made substantial contributions to understand the dynamics and structure of the middle atmosphere, important questions, of which a few are highlighted in this conclusion, still need to be answered.

This overview, although not exhaustive because of space limitations, has particularly evolved from conversations and correspondence with many colleagues abroad, whose names occur in the reference list or are cited as personal communications. I sincerely acknowledge this fruitful support as well as the useful comments on the manuscript by Wayne K. Hocking, Ben B. Balsley and Alan H. Manson.

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Discussion

H. G. Muller (*Department of Physics, University of Sheffield, U.K.*). Noting the capability of VHF (MST) radar to measure small-scale dynamical features in the mesosphere, one should take a fresh look at alternative techniques relating to the same altitude region, such as meteor radar. Traditional monostatic meteor wind radar, for example, measures individual wind-vector components in separate locations such that the total wind is averaged over the distance between these. The separation is typically several hundred kilometres in the horizontal, resulting in rather poor spatial resolution. This inherent limitation has been overcome in the recently commissioned U.K. bistatic meteor radar system where simultaneous recordings are made from two locations situated almost on the same meridian.

Radar beams are directed NW and NE from Sheffield and SW and SE, respectively, from Aberdeen. The beams are arranged to overlap in the meteor region thus creating two discrete measuring volumes at the same latitude but spaced in longitude by about 7°. Wind-vector components are measured in each beam direction such that the full wind vector is obtained in each volume without appreciable smoothing. By the use of interferometers the spatial resolution is improved to a few kilometres contrasting sharply with the order of a few hundred kilometres in the case of monostatic radar.

Data samples recorded in the two weeks preceding this Meeting illustrate the extent of temporal and spatial structure of the winds in the upper mesosphere. A cross-correlation analysis of the zonal winds in the two measuring volumes described above showed marked peaks in the power spectra for periods of about 5, 3 and 2 days. It is thought that these are associated with planetary waves extending to the top of the middle atmosphere.

D. G. Andrews. Can the seasonal variations of electron density be quantified, and do they need to be taken into account in the interpretation of VHF radar measurements of the mesosphere? In particular, might they give a spurious seasonal signal in the heights of gravity-wave breaking?

J. Röttger. Electron-density profiles are, of course, needed to interpret the 'turbulence echoes' from the mesosphere. A few attempts were made to measure electron-density profiles, e.g. by incoherent scatter radar, together with 'turbulence' profiles by MST radar. These were only case studies, and I think that studies to evaluate the seasonal variation of electron-density profiles are needed. Care should be taken when directly transposing mesospheric MST radar echo intensity into turbulence. A better means of indicating the strength of turbulence would be to evaluate other spectral moments, such as Doppler width, or the r.m.s. fluctuations of velocity time series. When signals are not detected, it has to be considered if this is because of inappropriate electron-density profiles or variation of the breaking of gravity waves. My paper summarizes the needs and also the references where more details can be found.

M. E. McIntyre (*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, U.K.*). The standard ideas about deducing the vertical diffusivity K_{zz} of potential temperature from the turbulent dissipation rate ϵ seem to me difficult to justify; this may yet turn out to be an example where dimensional analysis is not as powerful as it sometimes seems. It is certainly plausible that when the radar sees a Kolmogorov inertial subrange in fully three-dimensional turbulence one ought to be able to be fairly confident about the value of ϵ. It is not so clear, however, how much reliance can be placed on formulae of the type

$$K_{zz} = c\epsilon/N^2,$$

where N is the buoyancy (Brunt–Väisälä) frequency and where the dimensionless constant of proportionality c is taken as some modest fraction of unity. Fixing c assumes a constant partitioning between viscous dissipation and potential-energy gain, and this is often taken as the basis for deducing K_{zz}. There is reason to suspect, however, that c may actually vary rather widely with circumstances. For instance, if breaking gravity waves are the cause of the turbulence, c might well be sensitive to the degree of supersaturation of the waves. To be sure, the formula just quoted is believed to derive some support from laboratory measurements, but experts on the laboratory techniques tell me that the measurements are difficult, in part because of wall effects. It is also difficult to vary the way in which the turbulence is generated. There is some further discussion of how sensitive the behaviour of c might be in the recent Enrice Workshop proceedings (Visconti 1987).

Reference

Visconti, G. 1987 Transport processes in the middle atmosphere. In *Proc. NATO Workshop, Enrice, Sicily, November 1986*. Dordrecht: Reidel.

J. Röttger. The referred formula to determine the eddy diffusion coefficient K is based on some earlier publications of Weinstock, and is frequently used as a tool to obtain a most appropriate estimate of K. The values of the constant c of course vary quite a bit in the literature, and I agree that more work is needed to reduce its uncertainties.

In the case of wave-breaking events and the resulting strong turbulence it is also questionable to me how the Brunt–Väisälä frequency N is determined. It may lead to a total breakdown of the basic criterion for the referenced formula. However, I think that quite a few turbulence events seen by VHF–MST radar may be regarded as some kind of fossil turbulence in stable stratifications or just caused by dynamic instability of long-period waves (as explained in my paper). The criterion using N^2 then should be valid. However, in addition to the uncertainty of the constant c, we also have to know the thickness of the turbulence layers, which frequently may not be resolvable with the VHF radars. We, thus, can regard any value of K only as the best estimate, presently achievable, and should avoid final conclusions.

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