4. TECHNIQUES FOR STUDYING GRAVITY WAVES AND TURBULENCE (Keynote Paper)

M. A. Geller

NASA Code 964
Goddard Space Flight Center
Greenbelt, Maryland 20771

In the 1960s, there was great interest in studying gravity waves and turbulence in the middle atmosphere. The main emphasis at that time was to look at small-scale observed structures in the wind and temperature fields and to understand the relation between observed chemical composition and "eddy diffusion." The idea that internal gravity waves can be important in generating turbulence in an otherwise stably stratified medium was also being pursued during this period as was the idea of internal gravity waves providing a medium of physical communication between distant regions of the atmosphere. During the 1970s and 1980s it has become more fully appreciated how important it is to understand the interaction of gravity waves and turbulence with the large scale flow sufficiently to be able to parameterize these effects in global models of the middle atmosphere.

To understand this more fully, let us consider what the zonally symmetric structure of the middle atmosphere would be if differential heating was present but the effects of wave motions and mechanical dissipation were absent. An acceptable mathematical solution would be that of radiative equilibrium with a balanced thermal wind. The form of this solution state for solstice conditions is shown in Figure 1 (taken from GELLER, 1983). Obviously, this solution gives a winter stratosphere that is much too cold and a summer mesosphere that is much warmer than the winter mesosphere which is contrary to observations. Also, both the winter westerlies and the summer easterlies are much too strong and do not form closed jet structures as are observed. There is no vertical or meridional wind in this solution state since the local heating rates and accelerations are everywhere zero. It should be pointed out that this solution state is not an acceptable physical solution state since it is unstable due to the very large lateral wind shears.

If we now impose mechanical dissipation in the form of a Rayleigh friction acting on the mean zonal wind state (still remaining in a zonally symmetric framework), we get results shown in Figure 2 (also taken from GELLER, 1983) which are much closer to the observed state of the middle atmosphere. Physically, this altered solution results by the drag on the zonal flow diminishing the mean zonal flow and requiring a zonal accelerative effect to counter the drag's decelerative effect. This sets up a summer to winter meridional flow upon which the Coriolis torque produces the required accelerations. By continuity, a rising motion is set up in the summer hemisphere and a sinking motion in the winter hemisphere which, in turn, elevates the winter middle atmosphere temperatures and reduces the summer middle atmosphere temperatures to be more in line with observations.

It is believed that much of this mechanical dissipation has its source in gravity waves breaking into turbulence. A cartoon of this process is illustrated in Figure 3 (GELLER, 1983). Gravity waves tend to grow exponentially with altitude as is shown and give rise to a vertical flux of horizontal momentum that is constant with altitude until the breaking level where the wave becomes statically or shear unstable. Above this breaking level, the wave amplitude ceases to increase with height giving rise to a diminished magnitude of the momentum flux. This tends to accelerate (or decelerate) the mean zonal flow so as to bring the flow in this region toward the wave's phase velocity

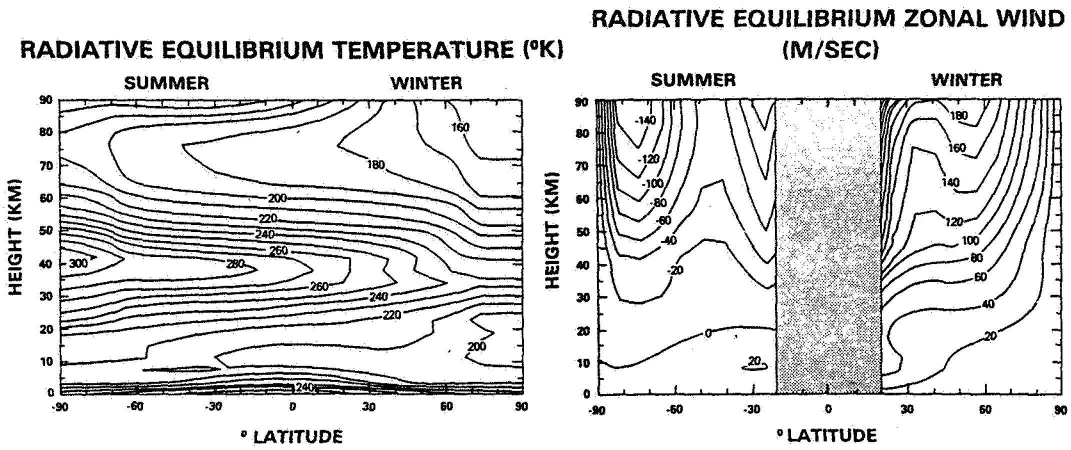

Figure 1. (Left) Calaculated radiative equilibrium temperatures. Units are K. (Right) Geostropic mean zonal winds calculated from the radiative equilibrium temperatures shown above. No values are shown near the equator because of the inapplicability of the geostropic formula there. Units are m/s, and westerly winds are positive while easterly winds are negative. (from GELLER, 1983.)

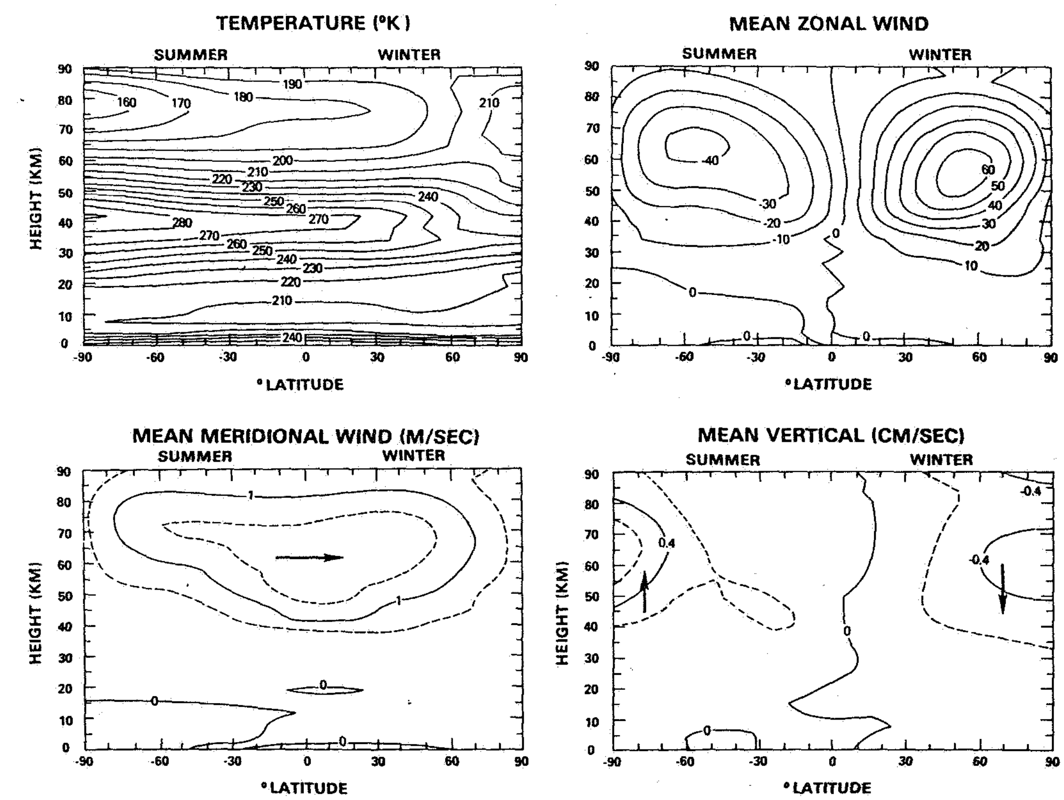

Figure 2. Model calculated zonally averaged temperature field in K (left-top); mean zonal wind in ms^{-1} (right-top); mean meridional wind in ms^{-1} (left-bottom); and mean vertical motion in cm s^{-1} (right-bottom).

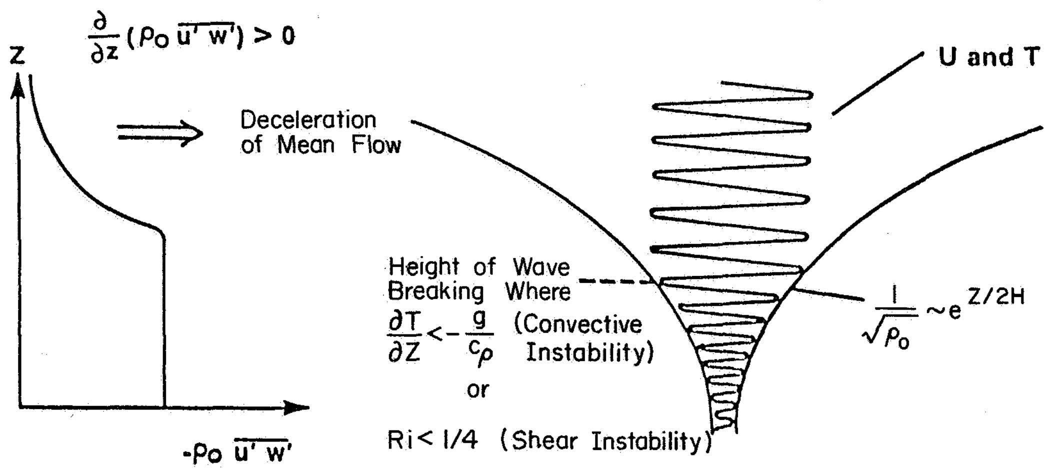

Figure 3.

which should be equal to the mean zonal flow velocity in its source region. Given that these gravity waves have their source in the troposphere where the zonal winds are relatively weak, the fast moving middle atmosphere flow will experience a drag. Gravity waves are thought to be essential to produce these effects since the other candidate, stationary planetary waves, are virtually absent in the summer hemisphere, but, as we have seen, mechanical dissipation is required in both hemispheres.

The mathematical basis for this mechanism was introduced by LINDZEN (1981). His formulae for the wave-induced drag and diffusion are shown in equations (1) and (2), respectively.

$$-\frac{1}{\rho_0}\frac{d}{dz}\rho_0\overline{uw} \approx \frac{-k}{2H}\frac{(\overline{u}-c)^3}{N(1+\ell^2/k^2)^{3/2}}\Bigg|_{\substack{\text{eval at}\\ z=z_{break}}} \tag{1}$$

$$D_{eddy} \approx \frac{k|\overline{u}-c|^4}{N^3(1+\ell^2/k^2)^{3/2}}\left[\frac{1}{2H} - \frac{3}{2}\left(\frac{1}{\overline{u}-c}\frac{d\overline{u}}{dz}\right)\right] \quad \text{eval above } z_{break} \tag{2}$$

In equations (1) and (2), k is the east-west wave number; ℓ is the north-south wave number, $\overline{u}$ is the eastward mean flow; c is the gravity wave phase velocity; N^2 is the Brunt-Vaisala frequency squared; H is the scale height; z is the altitude; ρ_0 is the background density; $\overline{uw}$ is the covariance of the eastward and upward gravity wave velocity; and z_{break} is the altitude at which the wave plus environmental lapse rate exceeds the dry adiabatic lapse rate of 9.8°C/km. MST radars appear to have the capability of observing $-\frac{1}{\rho_0}\frac{d}{dz}(\overline{uw})$ by the methods of VINCENT and REID (1983), for example, as well as D_{eddy} by measuring $C_n{}^2$, for example. They also can measure $\overline{u}$ and $\frac{d\overline{u}}{dz}$. One thing we will wish to discuss is how the remaining terms on the right-hand side of equations (1) and (2) can be either measured or inferred. This line of research will allow us to relate the theory of gravity wave breaking more closely to observations. Of course, LINDZEN'S (1981) formulation was only the beginning of theoretical formulations on this subject. Other factors to be considered are now becoming evident. These include the heat transports in breaking gravity waves (SCHOEBERL et al., 1983); the geographical nonuniformity of gravity wave propagation to breaking altitudes (SCHOEBERL and STROBEL, 1983); and nonlinear interactions among the gravity waves (WEINSTOCK, 1982).

MST radars represent a most powerful technique for obtaining the needed parameters for gravity-wave-induced drag and diffusion effects as well as measuring wave accelerations and diffusion directly. During this workshop, we will be discussing several of the factors relating to these measurements. We will be discussing the following topics as well as others that will arise:

(1) Required horizontal, vertical and temporal resolution.
(2) Wavelength dependence of the turbulence spectrum.
(3) Existence of a persistent background of turbulence.
(4) Determination of vertical and horizontal wavelengths of gravity waves.
(5) Parameterization of Fresnel returns.
(6) Minimization of bias and errors due to sampling and short-term fluctuations.
(7) Relationship of strength of turbulence to the received power.

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ISSUES AND RECOMMENDATIONS

INTRODUCTION

It is now generally accepted that gravity waves and their associated breaking into turbulence are very important in producing the overall picture of middle atmosphere global dynamics and associated transport. It is also accepted that the ST and MST radar techniques play an important role in assessing these effects. During the cause of this meeting, we have focussed on some important issues that arise in applying the ST and MST techniques to the study of gravity waves and turbulence.

(b) Issues

1. Eddy Diffusivities in the Lower Stratosphere: ST radars find effective eddy diffusivities of $\sim 0.1\ m^2s^{-1}$ in the tropical lower stratosphere. This is about one order of magnitude larger than previous analyses of aircraft observations have indicated. This discrepancy is presently unresolved and deserves further attention.

2. Turbulent Layering: There commonly exist long-lived thin turbulent layers of large horizontal extent ($\sim$100 km) in both the stratosphere and mesosphere. This requires theoretical explanation.

3. Validity of Homogenous and Isotropic Turbulence Theory: Given the fact that the VHF radars commonly probe eddy sites that are comparable to the thickness of thin turbulent layers, it is questionable if the formulations of homogenous and isotropic turbulence can be used to interpret these observations. Further work is required on this situation.

4. Monochromatic Gravity Waves: Much of the analysis of gravity waves takes place on the rather rare occasions when significant energy is found in almost monochromatic wave activity. Given that these events occur infrequently, it is questionable whether their analysis yield results that are representative of average atmospheric behavior.

(c) Recommendations

1. Programs to Verify Radar Measurements of Turbulent Parameters: We recommend increased activity toward using in situ aircraft, balloon, and rocket techniques to achieve simultaneous measurements of atmospheric turbulent parameters with ST and MST radars.

2. Colocation of Ground-Based Instrumentation with MST Radars: Given that MST radars are powerful major ground-based facilities but that they produce incomplete observations of atmospheric parameters by themselves (e.g., wind only and the 40-60 km gap), we recommend that other ground-based instrumentation (e.g., lidar, meteor radar, and partial reflection drifts) be colocated with major MST radar facilities.

3. Needed Spatial and Temporal Resolution: Given that gravity wave periods down to several minutes exist and that time averaging the radar signals before recording data is an irreversible process, we recommend that signal averaging before recording be done for as short times as is practical. In most cases, this should be a fraction of a minute.

ST and MST radars should be capable of range resolutions on the order of 150 m. The coarser the vertical resolution of MST and ST radars, the more difficult results are to interpret due to multiple returns.

4. $\overline{V^2}$ is Preferred Over C_n^2: Velocity variance measurements are preferred over C_n^2 measurements to characterize the energetics of atmospheric turbulence. Narrow beam width ($\sim$1°) systems are required to obtain measurements of $\overline{V^2}$ that can be easily interpreted.

5. Simultaneous Spectra: It is desired to obtain simultaneous spectra of horizontal and vertical velocities versus frequency and horizontal and vertical

wavelengths to resolve theoretical models.

6. HF Radars: We urge that the use of sensitive HF radars be explored for MST observations.

7. Radar Networks for Gravity Waves: We urge that networks of ST and MST radars be set up for a variety of spacings and representative of a variety of geophysical conditions to measure gravity-wave parameters.

8. Gravity-Wave Sources: We recommend that observational programs be planned to increase our understanding of gravity-wave sources.

9. Gravity-Wave Momentum Fluxes: Given the importance of understanding gravity wave drags on the large-scale flow, we recommend that MST radar facilities determine $\overline{V'W'}$ as a function of season and geographical location either by the methods of VINCENT and REID (1983) or by other methods.

10. Rotary Spectra: It is recommended that vector spectral analysis be applied to time series of the two components of horizontal wind at all available altitudes in order to determine the fraction of low-frequency gravity-wave energy associated with up-going and downgoing phase velocities.