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4. TECHNIQUES FOR THE STUDY OF GRAVITY WAVES AND TURBULENCE

(Keynote Paper)

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INTRODUCTION

Probably one of the most important achievements MST radars can make toward increasing our understanding of the dynamics of the atmosphere is to determine the exact relationship between the generation of turbulence and the sources of high shear or convectively unstable flows. An important theoretical tool through which we can begin to understand spontaneous generation of turbulence is the gravity-wave-breaking model. In this model, large amplitude gravity waves produce local regions where the Richardson number $(N^2/[U_z]^2)$ is less than 1/4 thus giving rise to turbulent flows. Thus the appearance of turbulent layers can often be interpreted as a breaking-gravity-wave signature.

Even though the techniques for studying gravity waves and turbulence may be quite different (and historically have resulted in somewhat separate bodies of literature), it is clear from the wave-breaking model that the phenomena are intimately linked. The techniques for measurements of gravity wave flow fields and turbulent regions by MST radar should show cognizance of some of the theoretical questions raised by the wave-breaking model.

(a) Determination of Turbulent Structures

Preliminary efforts have been made to categorize turbulent phenomena observed by high power radars (e.g., ROTTGER et al., 1979). Turbulent patches often appear as distinct layers which agrees well with the monochromatic gravity-wave-breaking model. Single bursts of turbulence are more enigmatic, however. They may result from superposition of gravity waves or other unknown processes. More work can be done toward classifying and expanding the turbulent layer morphology. How fast do the layers grow; what is their depth; how long do they persist; what is their frequency of occurrence; and can they be associated with gravity-wave events?

(b) Spectral Measurements of Wind Fluctuations

Initial attempts have been made to measure the energy spectrum associated with the horizontal motions (CARTER and BALSLEY, 1982). They found that the power law dependence showed -5/3 behavior suggestive of Kolgomorov's inertial subrange for turbulent motions. This result is reasonable for smaller scale eddies, but one would not expect theories of homogeneous turbulence to apply necessarily to the larger scale convective motions touched off by gravity-wave passage. Furthermore we would, a priori, not expect the gravity-wave spectrum itself to exhibit the -5/3 behavior. The fluctuation spectrum may "break" at larger wave numbers toward a different power law behavior as predicted by saturation theories of gravity waves or it may not exhibit any tendency at all. Clearly, important information on small-scale processes can be gained by measurement of the spectrum.

(c) Measurements and Interpretation of the Heat and Momentum Flux

Probably the greatest impact MST radars can have on our understanding of the general circulation is an accurate measurement of the climatology of the upward flux of momentum into the mesosphere $(\overline{u' w'} + \overline{v' w'})$ and the vertical convergence of that flux. The transport of heat by the turbulence induced by breaking waves is also of critical importance but can probably only be measured using an MST radar-lidar configuration.

Using a clever multibeam configuration VINCENT and REID (1983) have directly measured the momentum flux and found a surprising amount (1/3) of the transport in the high frequency gravity-wave field. This momentum flux may also include local transport of momentum by turbulent eddies acting on the basic shear which, of course, would not contribute to the net deceleration of the mesosphere. This may be the source of the momentum transport associated with high frequency motions.

In order to separate local transport of momentum from the upward flux of (psuedo) momentum from the troposphere, the layer fluxes should be carefully evaluated. It may also be possible to separate turbulent transport of momentum from transport by waves using the dispersion relations as a "wave transport" criteria.

(d) Relationship Between Isolated Turbulent Regions to the General Turbulent Background

As alluded to in the previous sections, the average turbulent background can produce important transports of heat, momentum and constituents. Some observers report semipermanent regions of turbulence in the upper mesosphere. How is this turbulence maintained (if a background level indeed exists)? Are there special locations for the formation of permanent turbulent layers?

(e) Determination of Vertical and Horizontal Wavelengths of Gravity Waves and Their Spectral Measurements

The development of a climatology of gravity waves in the mesosphere and stratosphere is most critical to our understanding of the circulation of that region. Information on both the horizontal wavelengths and relative frequencies are needed to determine the fluxes of momentum. Several methods are currently being used to determine directly the horizontal wavelengths including coincident spatial measurements and multibeam techniques.

The relative frequency of the gravity wave can be determined from the vertical wavelength via the dispersion relation or by independent measurement of the phase speed and background wind. The amplitude spectrum verses vertical and horizontal wave number is also useful since this can be theoretically related to the momentum transport. In addition to the local climatology of gravity waves, a global climatology is needed, and MST measurements need to be made at a variety of sites and under various conditions (e.g., summer, winter, etc.). To reiterate, since the origin of turbulence in the middle atmosphere can be linked to wave breaking, the study of gravity wave passage and subsequent turbulence formation leads to insight into both processes.

SUMMARY AND RECOMMENDATIONS

The study and measurement of gravity waves and the study of turbulence are not separate topics. The development and generation of low Richardson number flows which produce turbulent fields occurs through the saturation and/or interaction of gravity waves. It is the turbulent eddies from which the MST echo is derived. Thus it is important to determine if the "frozen turbulent field in a background flow" approximation is a valid assumption or whether the radar is measuring a property of the turbulent generation mechanism (i.e., the wave).

High power radars in the GHz frequencies have the capability of studying turbulence generation. Especially interesting are the detection of K-H CAT's eye structures. These structures are differentiated from other turbulence systems (e.g., convection) by their aspect ratio between the vertical and horizontal scale (about 1:6 ideally). Unfortunately the K-H billows cannot be detected until fully developed and thus the theory from which the aspect ratio is derived may no longer apply.

Another approach to studying both the turbulent and gravity-wave field is the compilation of spectra. Spectra are useful in a number of circumstances: first, the existence of spectra for the random fluctuation differentiates the kind of turbulent approximation and the mixing processes which may be important. For example, if the spectrum is characteristic of 2-d turbulence (horizontal) then vertical mixing is minimized. Also, 2-d turbulent spectra implies transfer of energy to large scales from smaller ones. If such transfer exists then turbulent energy may be transferred back to the gravity-wave motions.

Second, a buoyancy wave spectra contains implicit information about the distribution of energy within the gravity-wave field. The buoyancy wave spectra could be separated from the 2-d turbulence spectra by an examination of the fluctuations of the vertical velocity (2-d turbulence shows no vertical motion fluctuations). Unfortunately, nature may not be so reasonable as to present a pure 2-d turbulent field so it may, in practice, be difficult to separate the two spectra. It was also suggested that energy partitioning might be used to discriminate between the buoyancy spectra and the 2-d spectra. But this may also be difficult in practice. The buoyancy (gravity) wave spectra may also be hard to measure accurately without knowledge of the background wind, so to correct the observed frequency to the intrinsic frequency.

Finally, there have been a number of proposals that a universal gravity-wave spectrum exists in the atmosphere in analogue to the Garrett-Munk oceanic spectra. Independent constructions of spectra at various MST sites could yield important information on the global morphology or universality of spectra.

In contrast to the statistical approach of spectra construction, identification and measurement of individual gravity waves helps us understand forcing mechanisms and local polarization of gravity waves. Unfortunately, the identification of single monochromatic events with spaced receivers seems to be very difficult as gravity waves of different wave number and phase speed are often superimposed. Stratospheric measurements have been made only under the most ideal conditions when lee wave contamination was minimal.

The average momentum fluxes due to gravity waves and turbulent mixing of shear is somewhat easier to determine than the identification of individual waves. Furthermore, this quantity is probably most useful to large-scale modelers. However, care must be exercised in the measurement method so that bias toward certain wavelength gravity waves is not made. Mesospheric results indicate that most of the momentum flux is carried by high frequency short-scale gravity waves in summer, but larger scale planetary waves may contribute during winter.

Finally, it was pointed out that measurement of turbulent diffusion coefficients from radars can be misleading as turbulence is generated by breaking gravity waves between stable layers so the mixing is restricted to short vertical distances.

RECOMMENDATIONS

1. To study the generation of turbulence both the vertical and horizontal resolution need to be improved. This type of study can have a direct impact

on the measurements made by MST radars. Vertical resolution of 100 m in the mesosphere and 10 m in the stratosphere and troposphere, and horizontal beam widths of 1° - 2° as well as limited integration times (10-20 s) are required. Doppler velocities resolution of 10 cm s^{-1} is needed.

2. The measurement of the fluctuation of different types at different altitudes, and location is needed. More theoretical work needs to be done to determine to what extent the spectra are due to forcing, weak wave interaction, strong wave interaction or can be characterized by two-dimensional turbulence. Since there is some indication of an anisotropic gravity-wave spectrum (more upward propagating waves than downward propagating waves) do the analogies to oceanic spectrum still hold up?

3. Attempts to define and observe individual gravity waves should continue. Of particular interest is the distribution of gravity-wave intrinsic frequencies (background flow corrected frequencies) by horizontal wave number at different sites. We should also try to determine major sources of gravity waves.

4. Momentum flux measurements at different locations should be made both in the stratosphere and mesosphere and over varying topography and climatic conditions. A global morphology of the momentum flux and mean wind field ($\overline{u}$, $\overline{v}$, $\overline{w}$) would be very useful.