4.2A SPECTRAL MEASUREMENTS OF TURBULENCE AND GRAVITY WAVES

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Recently, it has become widely recognized that gravity waves play an important role in determining the large-scale circulation of the middle atmosphere (FRITTS et al., 1984). This realization has come about, in large measure, from the realization that Rayleigh friction plays an important role in the dynamics of the middle atmosphere. Since Rayleigh friction is intimately related to the saturation of vertically propagating gravity waves, an understanding of the saturation process has become a focal point for theoretical studies (FRITTS, 1984; WEINSTOCK, 1984).

With the advent of MST radar studies of the middle atmosphere, it has become possible to determine the spectrum of horizontal atmospheric velocity fluctuations over the range of scales which comprise the gravity-wave spectrum (BALSLEY and CARTER, 1982; LARSEN et al., 1982). It has been suggested (VANZANDT, 1982; DEWAN, 1979) that these spectra are comprised of buoyancy waves. However, the interpretation of these spectra is controversial as will be discussed below.

It has long been recognized (HODGES, 1967; BRETHERTON, 1969) that turbulence can result from the breaking of vertically propagating waves. This small-scale turbulence draws its energy from the internal wave field and, at the same time, provides a sink for internal wave energy. But there is another kind of "turbulence" that ought to be considered. This "turbulence" is the quasi-two-dimensional turbulence that occupies the same range of scales as the internal wave spectrum (GAGE, 1979; LILLY, 1983, LARSEN, 1983). Since it is associated with a reverse cascade of energy, it requires a small-scale energy source, and breaking waves would appear to provide the source that is required.

The relation between waves, quasi-two-dimensional turbulence, and ordinary small-scale three-dimensional turbulence can be examined more easily in the lower atmosphere than in the middle atmosphere. One reason for this is that, in the lower atmosphere, aircraft observations can be used to help understand the nature of the frequency spectra observed by MST radar. The results of several studies (LILLY and PETERSEN, 1983; NASTROM and GAGE, 1983) have recently shown that the aircraft spectra of horizontal velocity near the tropopause is very similar to Taylor-transformed frequency spectra of horizontal velocity obtained by radar. In addition, the aircraft also measures temperature and comparison of temperature and velocity spectra can aid in the interpretation of the nature of the observed spectra (GAGE and NASTROM, 1984).

MST radars can also be used to help understand the nature of the observed spectra. For example, vertical velocity spectra have been observed (ROTTGER, 1981; BALSLEY et al., 1983; ECKLUND et al., 1983) to be quite flat under "quiet" conditions and to fall off rapidly at periods less than the Brunt-Vaisala period. These features are strongly suggestive of a spectrum of internal gravity waves. If the spectrum of vertical motions is interpreted as an internal wave spectrum, it is possible to determine the magnitude and shape of the horizontal velocity spectrum of gravity waves and compare this spectrum with the observed spectrum of horizontal velocity fluctuations (GAGE and NASTROM, 1984).

Further clues to the nature of the observed horizontal and vertical velocity spectra may be obtained by studying the altitude variation of the horizontal and vertical spectra. It may be possible, for example, to demonstrate an increase in turbulent kinetic energy at altitudes where waves dissipate. In any event, such studies should elucidate the mechanisms by which the middle atmosphere is coupled to the lower atmosphere and clarify the role of gravity waves in this process.

Summary of issues to be resolved:

* Does there exist a "universal" spectrum of internal waves in the atmosphere analogous to the Garrett-Munk spectrum in the ocean?

* What are the sources and sinks of the atmospheric internal wave spectra? How do their dynamics differ from the dynamics of oceanic internal waves?

* Are the horizontal velocity spectra due to internal waves, quasi-two-dimensional turbulence, or some other cause?

* What is the altitude dependence of wave/turbulence spectra?

* What is the interrelationship of wave spectral amplitude, turbulence intensity, and the magnitude of the horizontal velocity spectra as a function of altitude?

* How are the joint dynamics of wave/turbulence processes best described as they relate to the coupling of the lower and middle atmosphere?

Spectral measurements needed:

* Comparisons of vertical and horizontal velocity spectra and their altitude variation.

* Climatological studies of vertical and horizontal velocity spectra.

* Comparisons of radar-derived spectra with spectra determined by other techniques.

* Vertical velocity spectra need to be obtained from flat terrain to determine the dependence of vertical velocity spectra on topography.

REFERENCES

Balsley, B. B. and D. A. Carter (1982), The spectrum of atmospheric velocity fluctuations at 8 km and 86 km, Geophys. Res. Lett., 9, 465-468.

Balsley, B. B., M. Crochet, W. L. Ecklund, D. A. Carter, A. C. Riddle and R. Garello (1983), Observations of vertical motions in the troposphere and lower stratosphere using three closely-spaced ST radars, Preprint vol., 21st Conf. on Radar Meteorology, Edmonton, Alta., Sept. 19-23, 1983.

Bretherton, F. P. (1969), Waves and turbulence in stably stratified fluids, Radio Sci., 4, 1279-1287.

Dewan, E. M. (1979), Stratospheric wave spectra resembling turbulence, Sci., 204, 832-835.

Ecklund, W. L., B. B. Balsley, M. Crochet, D. A. Carter, A. C. Riddle and R. Garello (1983), Vertical wind speed power spectra from the troposphere and stratosphere obtained under light wind conditions, Proceedings of Workshop on Technical Aspects of MST Radars, Handbook for MAP, Vol. 9, SCOSTEP Secretariat, Dep. Elec. Eng., Univ. Il, Urbana, 269.

Fritts, D. C. (1984), Gravity wave saturation in the middle atmosphere: A review of theory and observations, Rev. Geophys. Space Phys. (in press).

Fritts, D. C., M. A. Geller, B. B. Balsley, M. L. Chanin, I. Hirota, J. R. Holton, S. Kato, R. S. Lindzen, M. R. Schoeberl, R. A. Vincent and R. F. Woodman (1984), Research status and recommendations from the Alaska Workshop on gravity waves and turbulence in the middle atmosphere, Bull. Am. Meteorol. Soc., 65, 149-159.

Gage, K. S. (1979), Evidence for $K^{-5/3}$ law inertial range in mesoscale two-dimensional turbulence, J. Atmos. Sci., 36, 1950-1954.

Gage, K. S. and G. D. Nastrom (1984), On the spectrum of atmospheric velocity fluctuations and their interpretation, Paper 4.2-D, this volume.

Hodges, R. R., Jr. (1967), Generation of turbulence in the upper atmosphere by internal gravity waves, J. Geophys. Res., 72, 3455-3458.

Larsen, M. F. (1983), The MST radar technique: a tool for investigation of turbulence spectra, Proceedings of Workshop on Technical Aspects of MST Radar, Handbook for MAP, Vol. 9, SCOSTEP Secretariat, Dep. Elec. Eng., Univ. Il., Urbana, 250-255.

Larsen, M. F., M. C. Kelley and K. S. Gage (1982), Turbulence spectra in the upper atmosphere and lower stratosphere between 2 hours and 40 days, J. Atmos. Sci., 39, 1035-1041.

Lilly, D. K. (1983), Stratified turbulence and the mesoscale variability of the atmosphere, J. Atmos. Sci., 40, 749-761.

Lilly, D. K. and E. Petersen (1983), Aircraft measurements of atmospheric energy spectra, Tellus, 35A, 379-382.

Nastrom, G. D. and K. S. Gage (1983), A first look at wavenumber spectra from GASP data, Tellus, 35A, 383-388.

Rottger, J. (1981), Wind variability in the stratosphere deduced from spaced antenna VHF radar measurements, Preprint vol., 20th Conf. on Radar Meteorology, Boston, MA, November 30 - December 3, 1981, 22-29.

VanZandt, T. E. (1982), A universal spectrum of buoyancy waves in the atmosphere, Geophys. Res. Lett., 9, 575-578.

Weinstock, J. (1984), Gravity wave saturation and eddy diffusion in the middle atmosphere, submitted to J. Atmos. Terr. Phys.