Middle Atmosphere Program

[illegible]OK

[illegible]

[illegible] 2

TURBULENCE IN THE MIDDLE ATMOSPHERE: A REVIEW

R. F. Woodman

Arecibo Observatory
Arecibo, PR 00612

The stratosphere is characterized for being highly statically stable. It takes considerable energy to interchange parcels of air from different altitudes; thus, turbulence is normally inhibited. Wind shears of the order of 40 m/sec per kilometer are necessary to overcome the stabilizing effect of negative buoyancy if turbulence is to occur. Shears close to these values do exist in narrow but horizontally extensive layers as a consequence of internal gravity waves and the two-dimensional (horizontal) turbulent character of mesoscale stratospheric winds. Shorter wavelength waves, superimposed on these shears, make the local shear exceed the threshold (Richardson number < 0.25) for Kelvin-Helmholtz instabilities to occur and, in turn, to break into turbulence. In addition, the shear of these waves may be enhanced by a nonlinear unstable amplification of those gravity waves whose phase velocity matches the local.wind velocity. As a consequence, turbulence in the stratosphere occurs intermittently, in extensive layers from ten to a few hundred kilometers in extent, and only a few ten to a few hundred meters in thickness.

The above picture has emerged from a generalization of very high resolution radar observations of statically stable regions lower down in the troposphere and from less detailed measurements of the stratosphere proper.

Turbulence properties in the stratosphere can be measured, or inferred, using a variety of techniques. The techniques include: (a) *in situ* measurements of the turbulent velocity field by specially instrumented aircraft; (b) velocity field measurements using balloons (c) indirect measurements by means of rocket smoke trails (which determine regions where shear is sufficiently high for turbulence to occur), and (d) by means of powerful radars.

Radar techniques are potentially the best to characterize the morphology and energetics of turbulence, especially if provided with sufficient altitude resolution (see Figure 1). The power of radar echoes is a direct measure of index of refraction fluctuations due to turbulence for wavelengths within the inertial subrange. Furthermore, with the help of balloon measurements, or from good estimates of the local temperature gradients, it is also possible to infer from the power of the echoes the rate of turbulent eddy energy-dissipation. If the resolution of the radar is coarser than the thickness of the layer, some further support is necessary, namely, either the thickness of the layer or the percentage of the gated volume which is affected by turbulence. The latter has been

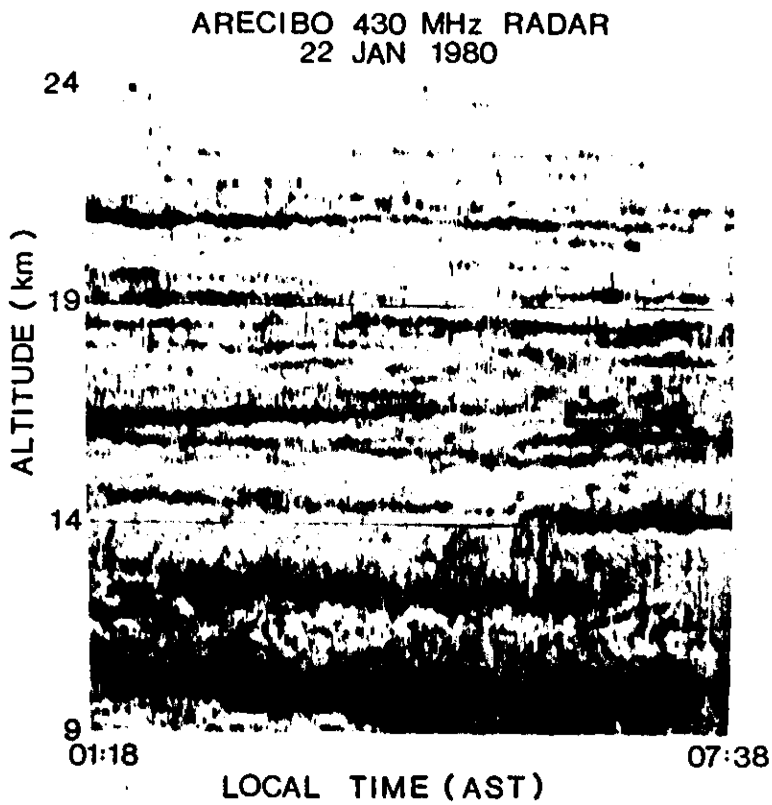

Figure 1. Radar echo-power of backscatter signals from turbulent fluctuations of clear air in the stratosphere and upper troposphere. Shade levels are every 4 dB. A piecewise linear trend has been subtracted with 0, 2, 5, and 12 dB of attenuation at 9, 14, 19, and 24 km, respectively. Results obtained with the 430 MHz Arecibo radar at 150 meter resolution. Unpublished material courtesy of Woodman, Rastogi and Sato.

estimated with success using, in addition, knowledge of the background shear. Radars, especially those with sufficiently narrow beams, can also measure the variance of the turbulence fluctuations in velocity, and hence their kinetic energy, through the Doppler widening of the frequency spectrum of the echoes.

Characteristic parameters of turbulence include the energy dissipation rate, ϵ, the variance of velocity fluctuation, u, the external morphology of the layers including their thickness, L, and their frequency of occurrence. These parameters are not completely independent. They are interrelated through theoretical energy considerations.

Energy dissipation is of interest because of the important role it plays in turbulence theory. Other parameters, including eddy diffusivity, can be theoretically derived from ϵ with varying degrees of accuracy. It is also an important parameter in its own right in numerical modeling of the atmosphere. No model can be considered realistic unless its energy balance agrees with observations. Velocity variance, u, and its spectrum are important in aviation in determining the maximum stresses turbulence can impose on aircraft. Space-time morphology is important in determining, in a more direct way, the effective eddy diffusion coefficient. The latter could play an important role in the vertical transport of contaminants in and out of the stratosphere.

Reported average energy dissipation rates within turbulent regions in the lower stratosphere range from 0.5 to 100 $cm^2\ sec^{-3}$ depending on the author, location, technique, and the type of averaging performed. The range of reported values for the velocity variance is more consistent, ranging from .25 to .5 m/sec for the maximum values; minimum values are lost by the sensitivity of the instruments. Percentage of occurrence, reported by aircraft (for $V > 0.15$ m sec) is of the order of 2-3% for flat land or oceans, and 5% for mountainous regions. Radar observations report higher frequency of occurrence; but, both measurements can be brought into better agreement if one considers the higher sensitivity of the radar. The thickness of the layers is distributed between a few tens of meters and a few hundred meters. The minimum thickness is still to be determined since the best resolution reported is of the order of 30 meters. Some radar echo strength measurements can be best explained if the layers are assumed to be as thin as 10 meters. The belief in their possible occurrence is encouraged by the fact that layers of no more than 5-10 meters have been detected in stable regions of the troposphere. Thickness of the layers is the most important parameter in determining the effectiveness of turbulence in the vertical transport of contaminants. It can also be shown that thickness and gradients determine the value of all the other characteristic parameters; hence the importance of developing very high resolution radars.

Estimates of effective turbulent eddy diffusivity for the lower stratosphere vary over 0.3-0.012 $m^2\ sec^{-1}$. This discrepancy, apart from being of one and a half orders of magnitude, has important consequences

VanZandt T. E., K. S. Gage and J. M. Warnock [1979], A statistical model for the probability of turbulence and the calculation of vertical profiles of turbulence parameters, Fourth Symposium on Turbulence, Diffusion and Air Pollution, Jan 15-18, 1979, Reno, Nevada.

Woodman, R. F., R. P. Kugel and J. Röttger [1980], *Radio Sci.*, *15*, 233.

Woodman, R. F. [1980], *Radio Sci.*, *15*, 417.

Woodman, R. F. [1980], *Radio Sci.*, *15*, 423.

Woodman, R. F. and A. Guillen [1974], *J. Atmos. Sci.*, *31*, 493.

Zimmerman, S. P., A. C. Faire and E. A. Murphy [1972], The measurement of atmospheric stability from 30 to -90 km, *Space Res. XII*, Academie-Verlag, Berlin, 615.