4.3A EXISTENCE OF A PERSISTENT BACKGROUND OF TURBULENCE

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Before the advent of VHF Doppler radars, it was generally believed, on the basis of direct measurements by balloons and aircraft and indirect measurements by incoherent radars, that turbulent layers in the free atmosphere have median thicknesses of at least 100 m. Since it was also believed that in the lower stratosphere only about 3% of the atmosphere is turbulent on the average (LILLY et al., 1974), then the mean separation between turbulent layers had to be at least 3 kilometers. If this were true, then a radar with 1-km range gates would detect an echo only about one third of the time and the fading of the echo strength would be very deep.

Instead, VHF Doppler radars with 1-km resolution usually detect echoes in every range gate up to the upper altitude of detectability. In the troposphere, echoes are detected in every range gate even with a resolution as small as 150 m. These results required that turbulence be much more uniformly distributed than had been thought. But since constraints on the total turbulent energy dissipation rate make it impossible for the entire volume of the lower atmosphere to be turbulent, the turbulence must be distributed among many, thin, relatively closely spaced layers. This distribution constitutes a persistent background of turbulence.

The principal mechanism for the generation of turbulence in the free atmosphere is thought to be shear instability in regions where the Richardson number Ri is less than 1/4. The existence of many thin turbulent layers then requires many thin regions of large shear. Such regions were suggested by vertical shear profiles from smoke trails (Figure 1) and high-vertical resolution balloon ascents during the 1960s. More recently, BARAT (1983) has used very high resolution balloon data to show that the turbulent layers do indeed occur in regions of large shear.

In order to interpret the early VHF Doppler radar measurements, VANZANDT et al. (1978) assumed that the total shear in the denominator of Ri is the sum of the steady background shear and a fluctuating mesoscale shear, which they described by a probability distribution. They then calculated the probability of occurrence of regions where Ri $\leq$ 1/4. Such regions occur more frequently where the background shear is large or where the background stability (N_B^2, the numerator of Ri) is small. They assumed, lacking evidence to the contrary, that the probability distribution in the troposphere is the same everywhere, independent of altitude or location, and similarly in the stratosphere.

In their model the mean thickness of turbulent layers was taken to be 10 m. This value might be in error due to deficiencies in the model or errors in the absolute calibration of the radar. Nevertheless, 10 m was so much smaller than the then generally accepted median thickness, that it did strongly suggest that the previous estimated thicknesses were too large.

Later more direct measurements confirmed that the median turbulent layer thickness is considerably less than 100 m. WOODMAN (1980b), using a 2380-MHz radar at Arecibo, found that the thickness of the echoing (turbulent) layers was usually not much larger than the altitude resolution used, that is, with 150 m resolution, they were often 150 m thick, with 60 m resolution, they were 60-200 m thick, and with 30 m resolution, they were 30-60 m thick.

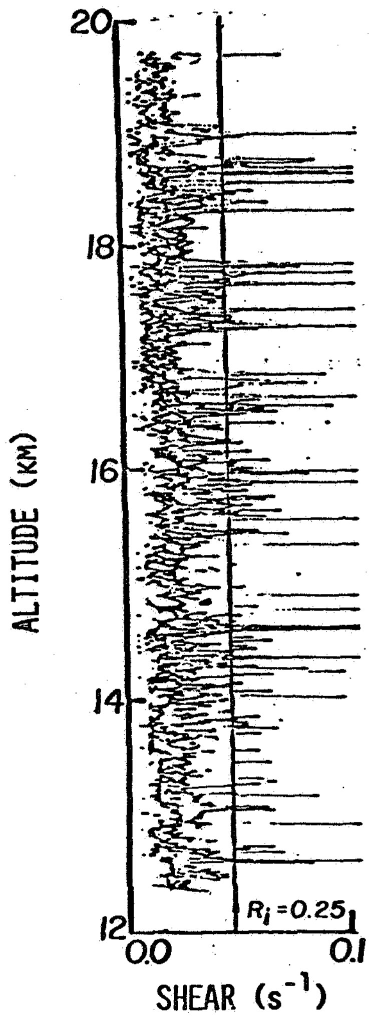

Figure 1. Superposition of eight vertical shear profiles from smoke trails with 25 m resolution. (Adapted from ROSENBERG and DEWAN, 1974.)

Indeed, when the earlier reports of direct measurements of turbulent layer thickness are examined, it is found that in almost every case the median or mean thickness reported is close to the resolution of the experiment. This suggests that the probability of occurrence of a turbulent layer of thickness in the range (L,dL) is a strongly decreasing function of L, at least for L larger than about 30 m.

In a very high resolution balloon experiment in the mid-stratosphere (27.5 to 29.5 km), BARAT (1982) found seven turbulent layers ranging in thickness from 3 to 240 m, with a median of 27 m and a mean of 56 m.

Although the VANZANDT et al. (1978) model provided a plausible scenario for the persistent background of turbulence it did not attempt any explanation for a persistent fluctuating distribution of mesoscale shears. Indeed, there was no generally accepted explanation for such shears.

Later VANZANDT (1982) showed that the mesoscale fluctuations of wind and temperature, hence of shear and stability, in the troposphere and lower stratosphere can be explained as the result of a spectrum of buoyancy (internal gravity) waves. The shape of this spectrum tends to be universal and, indeed, can be described by a slight modification of the GARRETT and MUNK (1972, 1975) model spectrum for oceanic internal gravity waves. There also appears to be a considerable degree of universality of the amplitude of this spectrum as a function of altitude, geographical location, etc., consistent with the assumption in the VANZANDT et al. (1978) model that the probability distribution of the shear fluctuations is invariant.

The universal shape of the oceanic internal waves spectrum is thought to be maintained by weakly nonlinear resonant wave interactions that cause a cascade of wave energy in frequency-wave-number space. The same process should operate in the atmosphere with some modifications. The scenario for energy flow is illustrated in Figure 2. Energy is put into the buoyancy wave field at vertical wave numbers smaller than β_* (vertical wavelength $\geq 1/\beta_*$). The sources of buoyancy wave energy are not well understood. They include wave generation by shear instability, on the upper and lower sides of jet streams, for example, generation of waves by convective storms, extraction of energy from lee waves by wave interaction, etc. The order of magnitude of the rate of energy input is not known even for the sources that have been identified.

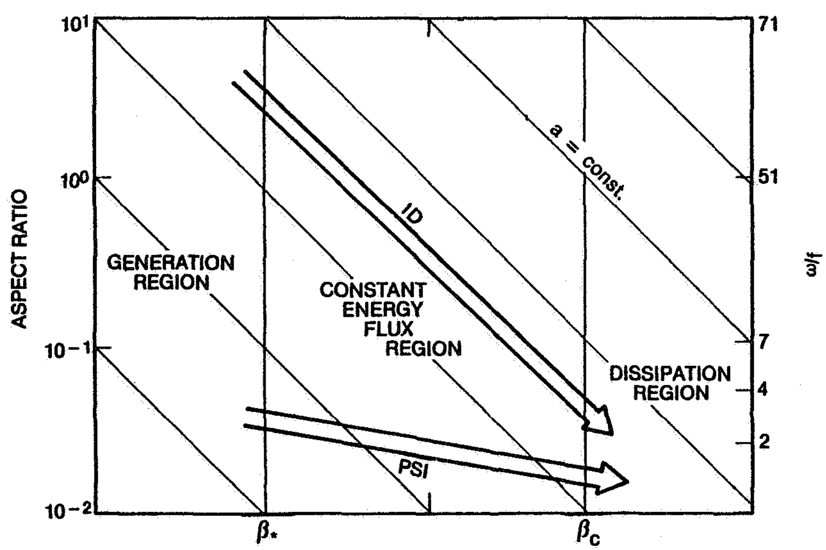

Figure 2. Schematic scenario for energy flow in the buoyancy wave field. *a* is the horizontal wave number. (Adapted from McCOMAS and MULLER, 1981.)

The energy is cascaded through the constant energy flux region by the wave interactions. McCOMAS and BRETHERTON (1977) showed that the dominant resonant wave interactions can be classified as "elastic scattering," which simply reverses the vertical phase velocity, and "induced diffusion" (ID) and "parametric subharmonic instability" (PSI), both of which move energy in frequency-wave-number space toward the inertial frequency, f = sin (latitude)/12 hr, and large vertical wave numbers (small wavelenghs). Since the variance of the shear versus log β increases about as $\beta^{1/2}$, as the energy moves to smaller and smaller vertical wavelengths the occurrence of shear instability (Ri $\leq$ 1/4) becomes more and more common. The critical wave number β_c is where the flux of energy by cascade from larger wave numbers can no longer keep up with the turbulent dissipation of wave energy. In the ocean $\beta_c \sim 1/10$ m (GARGETT et al., 1981); its value in the atmosphere is unknown, but the observed spectrum of horizontal wind versus β does not show any breakdown to at least 20 m, the shortest scale observed (R. E. GOOD, private communication).

This scenario also automatically results in long-lived, pancake shaped patches (blini) of turbulence, consistent with observations (ROTTGER and SCHMIDT, 1979; WOODMAN et al., 1981; SATO and WOODMAN, 1982; BARAT, 1983). Since the frequency spectrum is red, the dominant contribution to the shear at any particular scale is likely to be made by low-frequency waves, which have nearly horizontal surfaces of constant phase and small vertical phase velocities. Thus, most turbulent patches will be long-lived pancakes that move slowly upward or downward, as in Figure 3.

According to this scenario, because the stability is greater in the stratosphere than in the troposphere, the rate of occurrence of turbulence should be

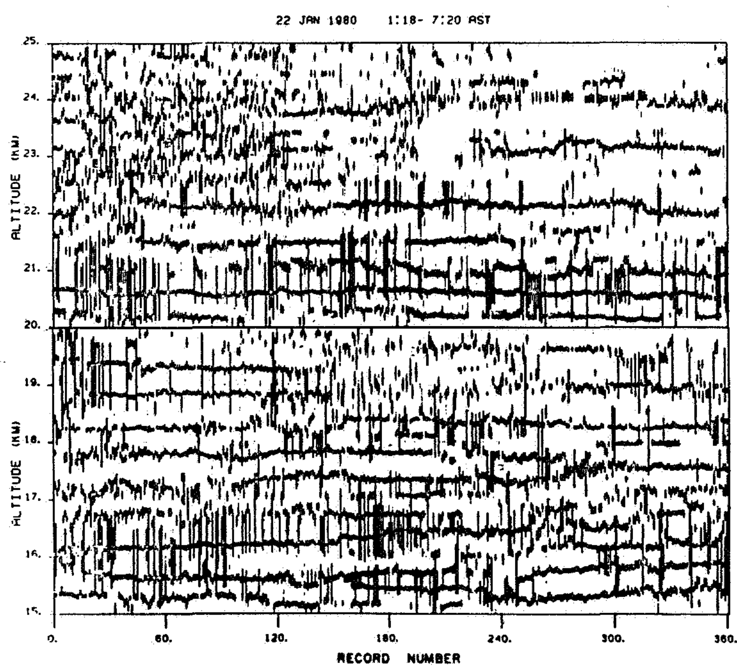

Figure 3. Locus of echo power maxima observed by the Arecibo 430-MHz radar with 150 m resolution. A turbulent layer is assumed to exist at every power maximum. (From WOODMAN et al., 1981).

less in the stratosphere. Also, the critical wavelength of $1/\beta_c$ will increase with increasing altitude due to the attenuation of buoyancy waves by the increaasing kinematic viscosity. This will result in fewer and fewer thin turbulent layers with increasing height. These predictions are qualitatively consistent with observations. With 150 m resolution, WOODMAN (1980) found that in the troposphere turbulence occurred in every range gate, but in the stratosphere above 16 km there were gaps. The thickness of these gaps increased with altitude, to about 1 km at about 24 km. The maximum height at which a turbulent echo was detected was 31 km. (At the greatest heights, the detectability of turbulence might have been strongly diminished by the approach of the inner scale of turbulence to the half-wavelength of the radar.) BARAT (1982) also found that turbulent layers are sparse in the middle stratosphere.

The foregoing constitutes a plausible scenario for the existence of a persistent background of turbulence. Other scenarios may be possible, but they have not been developed as far as this one has. The present scenario is generally accepted as the explanation for most, if not all, of the turbulence in the deep ocean (MUNK, 1981; GARGETT et al., 1981; DESAUBIES and SMITH, 1982). Nevertheless, many aspects of the scenario need to be quantified, not only in the ocean but even more so in the atmosphere. The MST radar technique can make crucial contributions to this study. It is the only existing technique that can be used to describe the morphology of occurrence of turbulence as a function of altitude, wind speed, shear, weather conditions, geographical location, etc. It is also the only technique that can describe the buoyancy wave spectrum versus frequency (BALSLEY and CARTER, 1982) and vertical wave number under a wide range of conditions. Such observations are essential to assess the degree of universality of the shape and amplitude of the buoyancy wave spectrum and the relation between the buoyancy wave spectrum and turbulence.

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