face locally deformed by thermals. While such mechanisms undoubtedly exist, any significant entrainment at a turbulent interface appears to be due directly to the large-scale motions.

Turner (1973) observes that mixing across a density interface occurs in the presence of large eddies which thrust into the undisturbed fluid and trap some of it; smaller scale motions are rapidly damped. Indeed, even the entrainment of neutrally buoyant fluid into a turbulent boundary layer appears to be due to large-scale motions, as originally proposed by Townsend (1956). Recent work reviewed by Laufer (1975) indicates that the dominant structures in any turbulent entrainment process are large-scale eddies which exhibit a considerable degree of coherence.

Turbulent entrainment is not analogous to molecular diffusion; it is not produced by small-scale turbulence crinkling the interface. Thus, mechanisms 1 and 4 proposed by Mahrt and Jensen are not expected to be important. This is supported by Turner's (1973) observations of a density interface when there is turbulence generated on both sides of the interface. He finds the behavior to be little different from that when only one side contains turbulent fluid. He concludes therefore that "the events which cause the removal of fluid are so rare that the two sides can be regarded as statistically independent." Entrainment is not a continuous, small-scale erosion process—it is dynamic and intermittent.

Mechanism 2 of Mahrt and Jensen involves entrainment by small-scale eddies at the boundaries of thermals which impinge upon the interface. They suggest that this is the origin of the thin wisps of entrained fluid which are observed adjacent to penetrating thermals. However, the rate of entrainment at a density interface is found to scale with the large-scale eddies (Turner, 1973). The detailed small-scale structure of the turbulence appears to be not important. Moreover, a propagating thermal or vortex tends not to entrain fluid across its leading face. The wisps of entrained fluid adjacent to a thermal could be simply displaced as the thermal penetrates into the undisturbed fluid.

Mechanism 3 is associated with mean shearing motions, which are not considered by Manton (1975). While shear is often present in the atmospheric boundary layer, there certainly are occasions on which it plays only a minor role. Then any entrainment is due to penetrative convection alone.

There is therefore considerable evidence supporting the hypothesis that, at least in the absence of mean shear, the main contribution to entrainment at the top of a convection layer is due to the direct action of the thermals penetrating the interface. Entrainment is caused by large-scale turbulent motions, not small-scale ones.

REFERENCES


Comments on “Stratospheric Long Waves: Comparison of Thermal Structure in the Northern and Southern Hemispheres”

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In their analysis of Selective Chopper Radiometer data Leovy and Webster (1976) emphasize that the temperature perturbations associated with planetary waves in the stratosphere move eastward during periods when their amplitude attains its greatest values. As a possible explanation for the correspondence between eastward motion and large amplitude they suggest the interaction between eastward traveling normal modes and forced stationary modes. While it may be desirable to describe this phenomenon in terms of known components, it is not necessary to make such an interpretation and, as will be noted here, it is possible to understand these observations in purely mechanical terms.

A fundamental explanation can be founded in the established relationship between westward slope of the height field and both upward energy flux and conversion from mean to eddy potential energy by planetary waves in the westerlies. This relation arises from the nearly hydrostatic and geostrophic nature of planetary waves and was first pointed out by Eliassen and Palm (1960)
for stationary waves, but should be qualitatively correct more generally for planetary waves in the stratosphere. An incipient disturbance may experience a 180° westward phase shift between the troposphere and the top of the stratosphere. Associated with this structure are an upward flux of energy by the pressure interaction mechanism and, if the zonal wind increases with height, a conversion from mean to eddy potential energy. These two energy sources support the growth of the wave in the stratosphere. If this structure were maintained, the wave would continue to grow until it completely altered the mean flow (a major warming?) or until it reached an equilibrium between its energy sources and its energy sinks due to barotropic exchange and to dissipation. What is most commonly observed, however, is that the wave grows for a time but almost simultaneously reduces its own growth rate by altering its structure. The most natural way for this to be accomplished is for the portion of the wave in the stratosphere to move eastward relative to the portion in the troposphere until the height field of the wave no longer has any slope in the vertical. In this configuration the upward flux and baroclinic conversions of energy are cut off and the energy of the wave rapidly decreases, primarily as a result of barotropic exchange with the mean flow. If the tropospheric portion of the wave remains relatively stationary, as might be expected for waves forced by surface features, then an eastward movement would be observed in the stratosphere during periods when the wave amplitude is large. This eastward movement would be even more apparent in the temperature field than in the height field, since the temperature phase begins at a position to the west of the height field, as is required for a hydrostatic westward-sloping height field, and then travels eastward arriving at a position coincident with the height field when the wave becomes vertical. The temperature wave thus must move eastward a greater distance than the height field during a cycle of growth and decay. Observations depicting the sequence outlined above have been presented by Hartmann (1976).

A simple explanation has been provided which suggests why eastward motion should be expected to occur in association with episodes of growth and decay of planetary waves in the stratosphere. It is based on the relations between wave structure and energetics. Although this explanation is not necessarily contradictory to that of Leovy and Webster, it is well, perhaps, to include here a few comments as to why it should be kept in mind while the discussion in terms of normal modes continues. First, the data presented to date show evidence that the active periods in the stratosphere are not truly periodic. On the contrary, the active periods appear to be more in the nature of "events" which occur at irregular intervals. Second, although normal mode analysis is very productive of understanding, it is not capable of describing the changes in zonal-mean structure which result from active periods and which generally occur on a time scale comparable to that of the eddies. These zonal mean changes are one of the interesting aspects of stratospheric dynamics and, ideally, our interpretation of the active periods should be flexible enough to encompass them.

REFERENCES


Reply

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The picture of the energy cycle of stratospheric waves and its relationship to the association between wave amplification and wave growth presented by Hartmann is very useful and is strongly supported by energetic studies such as that of Perry (1967), as well as by Hartmann's analysis of the 1973 SCR data. However, as is often the case, the energetics point of view provides valuable insight into how a process takes place, but does not by itself provide a fully satisfactory picture of the physical nature of the mechanism and consequently does not necessarily preclude other explanations. On the other hand, the normal mode viewpoint can provide a heuristic picture of mechanisms, but only if distinct modes do in fact exhibit their own distinctive responses to the appropriate components of forcing. The encouraging similarity between results of several theoretical