

Lindzen R S. Turbulence and stress owing to gravity wave and tidal breakdown.

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The breaking of vertically propagating internal gravity waves in the atmosphere is related to the generation of turbulent diffusion and the deceleration of the ambient flow. The effect of these processes on constituent transport, and on the reversal of the pole-to-pole temperature at mesopause levels, is dealt with as is the influence of the mean flow on the wave propagation and breaking. The latter was shown to account for seasonal differences. [The SC® indicates that this paper has been cited in more than 360 publications.]

Gravity Wave Breaking: Legitimizing Popular "Fudges"

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In the late 1950s and early 1960s rocket data provided evidence of large wave-like disturbances in the upper atmosphere. At first, these motions were attributed to turbulence, but they soon were identified as internal gravity waves. During the 1960s it was commonly assumed that these waves generated turbulence in the upper atmosphere and that this turbulence accounted for significant chemical transport. By the late 1960s it was recognized that the waves could grow to amplitudes so large as to render the waves unstable and that the resulting wave-breaking was directly responsible for the turbulence. The possibility that these waves could generate turbulence without breaking (albeit less effectively) was also recognized. In addition, it was realized that a source of friction was needed at mesopause levels in order to close the mesospheric wind jets and produce a reversal of pole-to-pole temperature gradients. (Note that at 50 km the summer pole is the warmest point while the winter pole is the coldest; however, by 80 km, the situation is exactly the reverse.) This friction was initially also associated with the assumed wave-generated turbulence; however, studies of gravity wave-mean flow interaction had, by the late 1960s, established that waves carried momentum directly. The point of all this is simply to note that virtu-

ally everything in this *Classic* was more or less known by the late 1960s. What this article did was to put this all into a coherent theoretical framework. In particular, it identified the conditions necessary for breaking and used these conditions to estimate magnitudes for turbulence and flow drag, noting that these two effects were distinct. The role of the mean flow in filtering and otherwise influencing the waves was also introduced. The paper noted the role of these effects in reversing the mesopause temperature gradient and in D-region chemistry. Subsequent papers refined and extended these results, noting the importance of the processes in the troposphere as well. In particular, in a later paper, I quantitatively sketched out the relevant sources of the gravity waves and noted the role of intermittancy.¹

Two points may be worth noting concerning the *Classic*. First, it had been clear to me how to synthesize the material concerning gravity wave breaking for almost a decade. From time to time, I tried to get graduate students to carry out the synthesis, but to no avail. I finally used the occasion of a short summer visit to the Naval Research Laboratory (in 1980) to carry out the synthesis and write the paper. New radar observations served as an additional stimulus. The work involved took about two weeks. The second point relates to the popularity of the paper. The fact is that atmospheric scientists had been invoking eddy diffusion and frictional drag on an ad hoc basis for decades. I suspect the popularity of the paper stems from the fact that it provided a theoretical rationale for what people were doing anyway. Be that as it may, the American Meteorological Society gave me their Charney Award in 1985 largely on the basis of this work.

Given the importance of turbulent diffusion and wave drag to problems ranging from numerical weather prediction² to upper atmosphere dynamics and chemistry, it should not be surprising that these topics remain the subject for much continuing research,^{3,4} though my own interests have increasingly focused on other problems. Somewhat discouraging (but nonetheless characteristic) is the fact that subsequent work has done little to make the theory more quantitatively precise. This is merely indicative of the fact that the data and understanding needed to go beyond the elementary treatment in the *Classic* was (and is) exceedingly great.

1. Lindzen R S. Gravity waves in the mesosphere. (Holton J R & Matsuno T, eds.) *Dynamics of the middle atmosphere*. Tokyo, Japan: Terra Scientific, 1984, p. 3-18.

2. McFarlane N A. The effect of orographically excited gravity wave drag on the general circulation of the lower stratosphere and troposphere. *J. Atmos. Sci.* 44:1775-800, 1987.

3. Luo Z & Fritts D C. Gravity-wave excitation by geostrophic adjustment of the jet stream. *J. Atmos. Sci.* 50:104-15, 1993.

4. Vireeck R A. A review of mesospheric dynamics and chemistry. *Rev. Geophys.* 29:1132-42, 1991.

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