Geophysical Research Abstracts,
Vol. 11, EGU2009-14092, 2009
EGU General Assembly 2009

Nonlinear Gravity Waves in the Middle and Upper Atmosphere: Instabilities, Turbulence, and Bores

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Gravity waves (GWs) exhibit a range of interactions and instabilities that span all wave amplitudes and intrinsic frequencies. These processes play increasingly important roles at higher altitudes due to wave amplitude increases with altitude. Linear and nonlinear theories provide useful guides to initial instability structures, growth rates, and evolution time scales, but typically fail to define finite-amplitude effects or responses for realistic environments. Numerical instability studies indicate a competition between 2D and 3D dynamics across the GW amplitude spectrum. Primary instabilities at small amplitudes and high frequencies manifest as 2D interactions transferring initial wave energy to GWs having smaller vertical scales and lower frequencies. 3D dynamics predominate at larger amplitudes, though both 2D and 3D dynamics contribute to rapid energy transfers. Nonlinear interactions and wave breaking at larger amplitudes yields large amplitude reductions, a broad inertial range of turbulence, and a large turbulent Prandtl number. The turbulence generation and cascade follow specific pathways, yielding turbulence that is strongly correlated with the gravity wave phase, highly variable in intensity, and remains highly anisotropic throughout the evolution. Significant GW amplitudes at higher altitudes also provide the environment, and the seed conditions, for the generation and sustained propagation of "mesospheric" bores that closely resemble similar large-amplitude responses observed at much lower altitudes.