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Mechanisms for spontaneous gravity-wave generation within a dipole vortex

C. Snyder (1), R. Plougonven (2), and D. Muraki (3)

(1) Mesoscale and Microscale Meteorology Division and Institute for Mathematics Applied to Geophysics, NCAR, Boulder, United States (chriss@ucar.edu), (2) Laboratoire de Météorologie Dynamique, IPSL, Ecole Normale Supérieure, Paris, France, (3) Department of Mathematics, Simon Fraser University, Vancouver, Canada

Numerical simulations a dipole vortex in rotating, stratifed fluid at small Rossby number reveal smaller-scale inertia-gravity waves embedded within and stationary with respect to the dipole vortex (Snyder et al. 2007). These waves appear to be an inherent part of the dipole solution, as they are insensitive to initial conditions and persist in a nearly steady state for many tens of days—in this sense, they are emitted or generated spontaneously by the dipole vortex. Similar waves have also been found in other dipole simulations, which differ in their numerical techniques and in the details of the dipole vortex (Viudez 2007, 2008; Wang et al. 2008). We investigate the source mechanism for these inertia-gravity waves.

Since the waves have small amplitude in horizontal velocity and potential temperature relative to the dipole, we consider the numerical simulations to be the sum of an approximate quasigeostrophic (QG) solution and a small deviation that may include waves as well as balanced "corrections" to the QG dipole. To leading order in their amplitude, the deviations satisfy linear equations, based on linearization about the QG dipole and forced by the residual tendency of the QG dipole (that is, the difference between the time tendency of the QG solution and that of the full primitive equations initialized with the QG fields). The linear equations accomodate two possible wave-generation mechanisms: either an instability of the dipole, which would appear as a growing, homogeneous solution, or forcing of inertia-gravity waves by the residual tendencies.

While numerical solutions of the homogeneous linear equations do reveal growing disturbances, they are nearly geostrophic, have length scales comparable to the dipole itself and grow too slowly to explain the the stationary waves in the full, nonlinear simulations. Instead, these growing disturbances represent balanced corrections to the QG dipole, which are to be expected since the dipole in the nonlinear simulations propagates more slowly than the QG dipole and along a slightly curved path.

The linear solution forced by the residual tendencies, in contrast, yields excellent qualitative agreement with nonlinear simulations for the packet of inertia-gravity waves at the leading edge of the dipole. It correctly predicts the scale and pattern of the wave crests and the fact that they are stationary relative to the dipole and have nearly steady amplitude. Quantitatively, the forced, linear solution overestimates the amplitude of the waves by a factor of 2.

This spontaneous generation of waves is broadly analogous to the production of sound by vortical motion as discussed originally by Lighthill, or of gravity waves in shallow water flows as explored by Ford and collaborators. But the inertia-gravity waves found in the dipole vortex differ in two important aspects from the predictions of the Lighthill/Ford theory: They are of smaller scale than the dipole rather than larger scale and they are confined within the dipole rather than appearing in the far field. Scale analysis of the dispersion relation for inertia-gravity waves provides qualitative explanations for the characteristics of the waves and why they differ from Lighthill/Ford theory.