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The mesoscale kinetic energy spectrum of a baroclinic life cycle

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The observed atmospheric kinetic-energy spectrum exhibits a transition between k^{-3} and $k^{-5/3}$ dependence at a scale of about 500 km. Despite two decades of research, the dynamics that lead to this transition remain uncertain. Proposed explanations for the -5/3 spectrum below 500 km range from an inverse cascade in nearly two-dimensional turbulence to a forward cascade produced by weakly nonlinear inertia-gravity waves or three-dimensional but highly anisotropic stratified turbulence.

We investigate the mesoscale energy spectrum within a high-resolution simulation of an idealized baroclinic wave, with horizontal and vertical resolution $\Delta x \approx 10\,\mathrm{km}$ and $\Delta z \approx 60\,\mathrm{m}$. Because it exhibits many realistic mesoscale features such as fronts, jets, and inertia–gravity waves (IGWs), this simulation allows us to study the fundamental mesoscale dynamics without the complicating effects of moist convection and topography. The natural question is whether such dynamics are sufficient to yield a kinetic energy spectrum similar to the observed.

The simulation exhibits a shallowing of the mesoscale spectrum with respect to the large scales, in qualitative agreement with observations, but this shallowing is restricted to the lower stratosphere. No transition in the power law occurs in the upper troposphere, despite the simulation having sufficient vertical resolution to capture the expected vertical scales of anisotropic stratified turbulence. At both levels, the mesoscale divergent kinetic energy spectrum—a proxy for the IGW energy spectrum—resembles a -5/3 power law in the mature stage. Divergent kinetic energy dominates the lower stratospheric mesoscale spectrum, accounting for its shallowing, but rotational kinetic energy dominates the upper tropospheric spectrum. The tendency equation for the kinetic energy spectrum shows that the lower stratospheric spectrum is not governed solely by a downscale energy cascade, but rather is influenced by the vertical pressure flux divergence associated with vertically propagating IGWs. Thus, the shallowing in the lower stratosphere has its source in the spontaneous excitation of IGWs by the larger-scale motions in the troposphere and near the tropopause.