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Atmospheric turbulence with energy sources at two disparate length-scales.

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The atmospheric kinetic energy is affected by two distinct sources at widely separated horizontal length-scales: baroclinic instability at wavelengths around 3000 km (synoptic scales), and convection at wavelengths between hundreds and a few thousand meters (mesoscales). Nastrom and Gage (1985) analyzed observations of the atmospheric energy spectrum as a function of horizontal wavenumber showing two power-law ranges: a steep -3 slope for the synoptic scale range and a shallow -5/3 slope for the mesoscale range. The -5/3 spectral slope was initially puzzling, as this was only anticipated for isotropic 3D turbulence, which does not apply to these scales.

High-resolution mesoscale model simulations demonstrate that convective systems are able to generate a background kinetic energy spectrum with a slope close to -5/3, like in the atmospheric mesoscales. This attributed to upscale transfer by Gage (1979) and Lilly (1983). We compare such meteorological models to idealized non-hydrostatic dry Boussinesq turbulence simulations with triply-periodic geometry, where such results are generally not obtained. We aim to study turbulence in as close as possible to the atmospheric context. To make it analogous to a typical meteorological model, we configure our simulations by using similar resolutions and an anisotropic grid. We also added a stable mean vertical shear flow profile and free-slip boundaries at the top and bottom. A first set of simulations took initial conditions as random buoyancy perturbations centered on an intermediate horizontal wavenumber. This caused a downscale cascade of energy, while producing a decaying peak that remained at the injection wavenumber. We were later able to produce the -5/3 spectral slope by instead specifying the initial buoyancy field as a series of aligned, localized structures, as used in previous meteorological studies (e.g, Sun et al., 2019). These structures produced a short-lived upscale transfer of energy. Additionally, it is to be noted that the -5/3 spectral energy slope was reproduced using the dry Boussinesq equations, suggesting that moist processes may not be central to these dynamics.

Lastly, we increase the horizontal resolution of our model configuration, while reducing horizontal diffusion. At the same time, we keep the vertical resolution and vertical diffusion the same. This changes the grid aspect ratio for our simulations, while moving closer to the isotropic grids typically employed in turbulence studies. We find that the -5/3 spectral energy slope is maintained in all those simulations, while the horizontal wavenumber extent of the slope and the upscale energy flux varies as a function of the horizontal resolution and numerical model diffusion. This also suggests that similar dynamics observed in meteorological models are somewhat robust to the grid aspect ratio.

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