A NEW FORMULATION OF THE SPECTRAL ENERGY BUDGET OF THE ATMOSPHERE, WITH APPLICATION TO TWO HIGH-RESOLUTION GENERAL CIRCULATION MODELS

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Abstract In order to investigate the dynamics of atmospheric turbulence, we have derived a new formulation of the spectral energy budget of kinetic and available potential energies of the atmosphere, with spherical harmonics as base functions. Compared to previous formulations, there are three main improvements: (i) the topography is taken into account, (ii) the exact three-dimensional advection terms are considered and (iii) the vertical flux is separated from the energy transfer between different spherical harmonics. Using this formulation, results from two different high resolution GCMs are analyzed: the AFES T639L24 and the ECMWF IFS T1279L91. The spectral fluxes show that the AFES, which reproduces realistic horizontal spectra with a $k^{-5/3}$ inertial range at the mesoscales, simulates a strong downscale energy cascade. In contrast, neither the $k^{-5/3}$ vertically integrated spectra nor the downscale energy cascade are produced by the ECMWF IFS.

THE ATMOSPHERIC HORIZONTAL ENERGY SPECTRA AND THE DOWNSCALE ENERGY CASCADE

The atmospheric horizontal spectra of velocity components and temperature show a robust $k^{-5/3}$ range at mesoscales (10-500 km) [6]. It still remains a challenge to reproduce this result in simulations. Some general circulation models (GCMs) [5, 4] and mesoscale numerical weather prediction models [8] reproduce quite realistic mesoscale spectra. Other GCMs, as for example ECMWF's weather prediction model Integrated Forecast System, produce mesoscale spectra significantly steeper and with smaller magnitude than the measured ones, even with relatively high resolution versions [7]. The inability of some GCMs to simulate realistic mesoscale spectra must have important consequences in terms of predictability, dispersiveness of ensemble prediction systems and, evidently, mesoscale numerical weather prediction. Even though one can now simulate realistic mesoscale spectra, it is still unclear what physical mechanisms produce them. Theoretically, the only convincing explanation of the $k^{-5/3}$ power law is the hypothesis that it is produced by an (upscale or downscale) energy cascade with a constant energy flux through the scales.

A NEW FORMULATION OF THE SPECTRAL ENERGY BUDGET

In order to investigate the energetics of the mesoscales simulated by GCMs, a new formulation of the spectral energy budget has been derived in pressure coordinates and using both scalar and vectorial spherical harmonics transforms. Our formulation is highly innovative since in contrast to the previous formulations, the Available Potential Energy (APE) budget is included, the topography is taken into account and the exact three-dimensional advection is considered. Moreover, the advection terms are split into spectral transfers and vertical fluxes, and the pressure term is split into adiabatic conversion and vertical flux.

PRESENTATION OF THE DATA AND THE MODELS

Using this formulation, results from two different high resolution GCMs are analyzed, the Atmospheric GCM for the Earth Simulator (AFES) [4] and ECMWF's weather prediction model Integrated Forecast System (IFS) [3]. The AFES is a climate model using a spectral advection scheme. It has been run at high resolution for research purposes. The horizontal resolution is T639, which correspond to a minimum wavelength of roughly 60 km. Hamilton et al. (2008) showed that the AFES reproduces many features of the atmospheric spectra, especially a realistic $k^{-5/3}$ power law at the mesoscales. ECMWF IFS is a model developed and used for operational deterministic forecast. It uses a semi-Lagrangian advection scheme with a horizontal resolution T1279, which correspond to a minimum wavelength of roughly 30 km.

RESULTS: TWO VERY DIFFERENT DYNAMICS

The spectral fluxes show that the AFES simulates a strong downscale energy cascade of $\Pi \simeq 0.8$ W/m^2. In contrast, the spectral fluxes for the ECMWF model are very small at the mesoscales. We have shown that this is due to a strong dissipation of kinetic energy at scales of the order of 2000 km. This anomalous dissipation at the synoptic scales could be related to the turbulent scheme, the wave drag and/or the semi-lagrangian semi-implicit numerical scheme.

The study of the spectra and their tendencies integrated over different layers reveals that in the AFES, the stratospheric mesoscales are not forced by upward propagating gravity waves but by the nonlinear cascade. In contrast to this, the stratospheric spectra of the ECMWF model are directly forced at the mesoscales by gravity waves propagating from the troposphere.

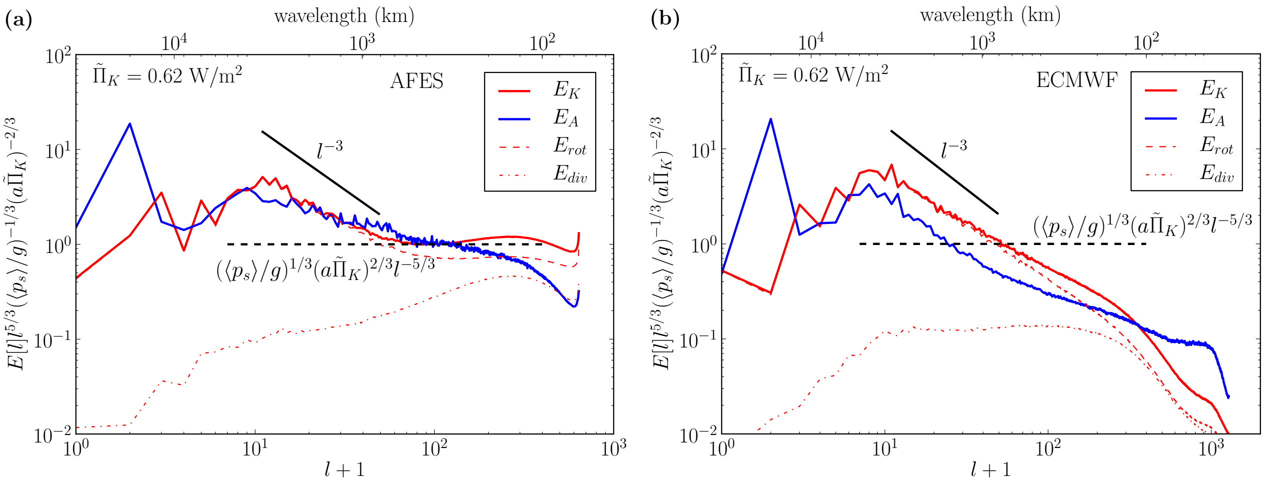

Figure 1. Non-dimensional compensated spectra versus total wavenumber for (a) the AFES T639 simulation and (b) the ECMWF IFS T1279 simulation. The black dashed line represents the prediction based on the existence of the cascade $E_K[l] = C(\langle p_s\rangle/g)^{1/3}(a\Pi_K)^{2/3}l^{-5/3}$, with $\tilde{\Pi}_K = 0.62$. The continuous straight line indicates the l^{-3} power law.

In figure 1 are plotted as a function of the total wavenumber l the non-dimensional compensated spectra $E[l]/E^*[l]$, where

$$E^*[l] = l^{5/3}(\langle p_s\rangle/g)^{-1/3}(a\tilde{\Pi}_K)^{-2/3},$$

is a prediction based on the existence of the cascade, a is the radius of the Earth, $\langle p_s\rangle$ the mean surface pressure and $\tilde{\Pi}_K$ the maximum of the computed kinetic energy flux at the mesoscales. Except at the planetary scales, the kinetic energy and APE spectra are of the same order of magnitude. For the ECMWF model (figure 1b), the ratio E_K/E_A is equal to 2 at the synoptic scales as predicted by the theory of quasi-geostrophic turbulence [2]. For the AFES model (figure 1a), the spectra at the mesoscales collapse on the prediction $E^*[l]$ (black dashed lines), indicating that the mesoscale $k^{-5/3}$ power law is due to the downscale energy cascade. In contrast, for the ECMWF model, the spectra at the mesoscales are much steeper and smaller.

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