Royal Netherlands Meteorological Institute
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Atmospheric kinetic energy exchange across scales

Horizontal resolution dependence in a global climate model

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Upscale transfer of kinetic energy (KE) from the sub-synoptic scales indicates the dynamical influence of these scales on the synoptic scales. We show a reduction of this upscale energy transfer at lower horizontal resolution even in the well-resolved range of scales. Furthermore, we quantify the KE budget and KE exchange at the transition between the resolved and dissipative range.

Introduction

A critical limitation due to the finite resolution of fluid dynamical models is the upscale coupling of parameterized scales on the resolved scales. In terms of energy, this coupling originates predominantly from the nonlinear advective terms in the energy equations and is usually described by a spectral transfer term that expresses the convergence of the energy flux at each wavenumber (= reciprocal scale). Consequently, the spectral transfer at an arbitrary wavenumber is then a source or sink but it does not say where the energy is either coming from or deposited to.

We extend the atmospheric 3D spectral energy budget from Augier et al. (2013) by introducing the spectral distribution $\tau_K^{l,l'}$ of the transfer function T_K^l, which quantifies the energy transfer at wavenumber l due to nonlinearities that involve wavenumber l' (including cross product terms with other wavenumbers). We apply this diagnosis to a global climate model to study the KE budget at various scales and the impact of horizontal resolution.

Key Points

Upscale KE transfer from (sub-)synoptic scales is reduced at low resolution (125 km), even though KE spectra suggest that these scales are well resolved

Transition of the KE budget between resolved and dissipative regime

Data

We compare two resolutions, T159 (125 km) and T799 (25 km), of SST-forced atmosphere-only runs in a global climate model (EC-Earth 2.2). We compute energy transfer for 8 snapshots from different runs of the model.

Formulation of KE budget

The KE budget for an arbitrary wavenumber l is well approximated by vertical integration of the following budget for an infinitesimal layer (Augier et al. 2013)

$$\frac{\partial}{\partial t}E_K^l \approx C^l + T_K^l + \frac{\partial}{\partial p}F_{K\uparrow} + D_K \qquad (1)$$

With C the generation of KE from APE, $\frac{\partial}{\partial p}F_{K\uparrow}$ the vertical divergence of the vertical flux of KE and D_K the dissipation. The dissipation can be estimated as a residual of the budget. The spectral transfer T_K^l arises from the 3D advection and is the only nonlinear term in equation (1), therefore the only term that permits energy exchange between wavenumbers. The sum of equation (1) over all wavenumbers equals the horizontal mean budget, in which the spectral transfer vanishes because $\sum_l T_K^l = 0$.

Interpretation of figure 1

Figure 1 depicts the net energy fluxes between wavenumbers vertically integrated over the troposphere (1022-196 hPa). Values along the l'-axis quantify the impact of l' on the spectral energy convergence along the l-axis. For example, the negative value at (x,y)=(l',l)=(10,20) indicates that the global distribution of the advection involving l'=10 (including cross-products with other wavenumbers) has the net effect of reducing the magnitude of the l=20 wave pattern of the wind. Due to nonlinearity it is not required that this removal of energy is deposited at the same wavenumber (l'=10). Yet, the apparent degree of antisymmetry about the $l = l'$ diagonal suggests that the majority is.

Upscale KE transfer

The black shapes in figure 1 (top, middle) depict an upscale energy transfer from the sub-synoptic scales to the synoptic and planetary scales. A subsequent further upscale energy transfer toward wavenumber l=3 is depicted by the white shapes.

From the difference between the resolutions (bottom panel), the positive values for the black shape with l' (x-axis) between 15-100 (wavelengths 2700-400 km) indicate a larger net upscale transfer from the sub-synoptic and mesoscale toward the synoptic scales for the higher resolution. This difference extends further upscale than would be expected on basis of the steepening of the T159 spectrum for l >30 (figure 3).

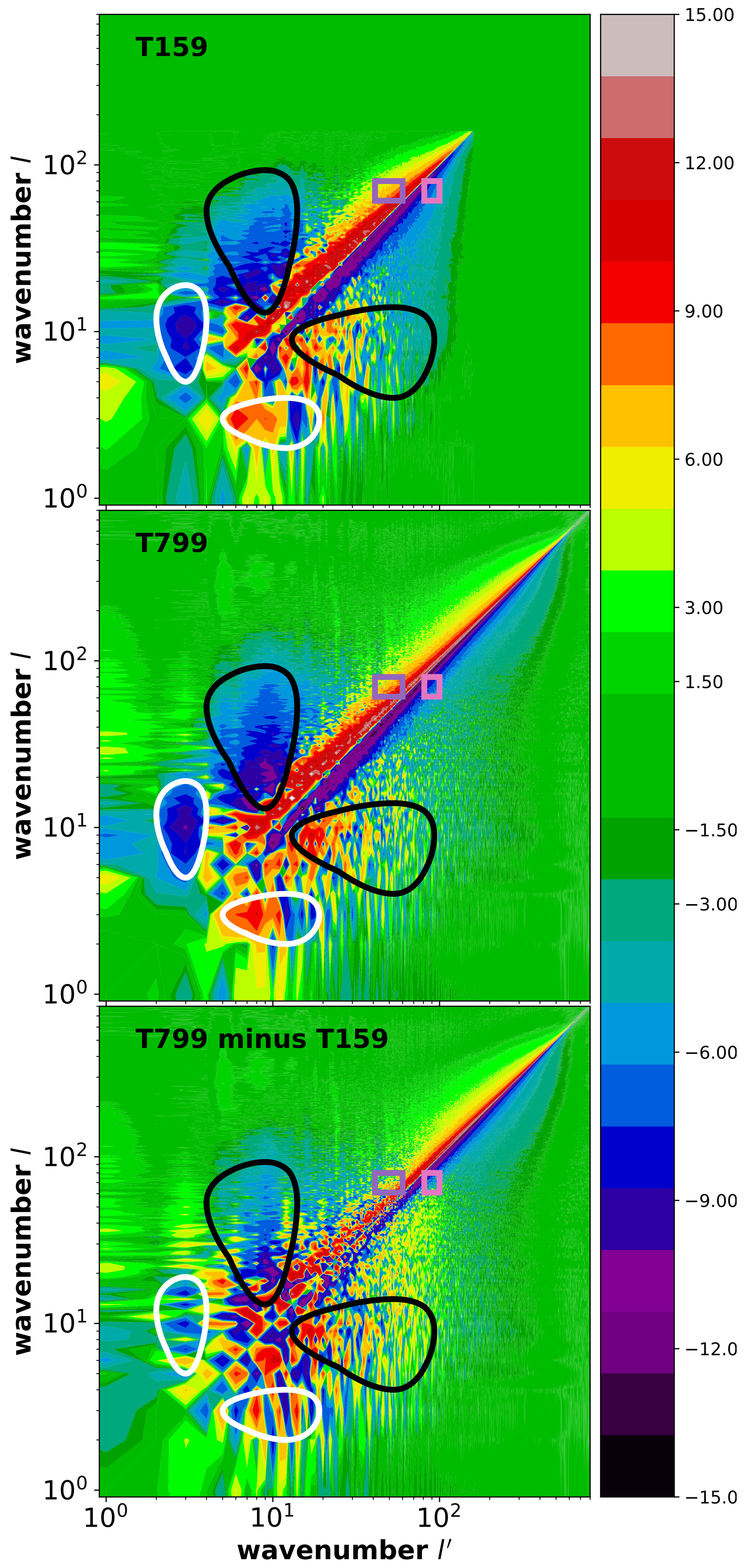

Figure 1: Nonlinear energy transfer between wavenumbers vertically integrated over the troposphere (1022-196 hPa). Values along the l'-axis quantify the impact of l' on the spectral energy convergence along the l-axis. An integral along the x-axis (over l') equals the conventional form of the KE transfer $T_K^l = \sum_{l'} \tau_K^{l,l'}$, which expresses the convergence of KE for each wavenumber. We have multiplied the energy flux (in W/m2) with the wavenumbers along each axis. This multiplication compensates for the area on a logarithmic scaling, thus preserving that the integral is zero.

Transition of the KE budget between resolved and dissipative regime

Downscale cascade Along the diagonal $l = l'$ in figure 1 we find a downscale KE cascade toward (near-) neighbouring wavenumbers that extents from the synoptic scales to the small unresolved scales. Figure 2 depicts the downscale cascade in the sub-synoptic and mesoscale as a bar plot (T799 left and T159 in the right panel) grouping the values in figure 1. For example, the annotated bars in the left panel denote the sum over the values within the corresponding squares for the T799 resolution. The total convergence of spectral energy exchange is shown as a white bar. As expected, the net nonlinear energy transfers are much larger terms and the convergence is only a small residual.

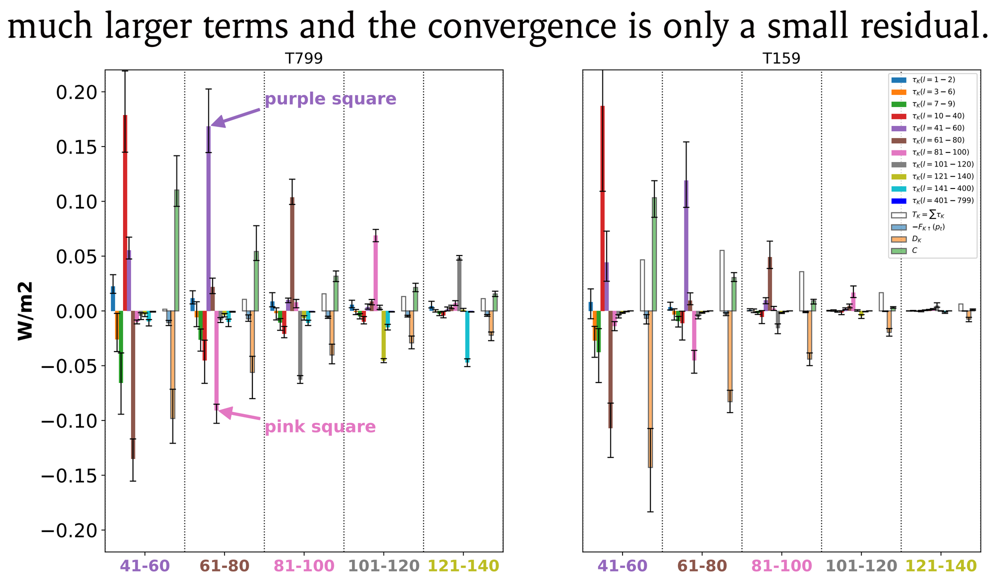

Figure 2: Nonlinear Energy transfer. Bars denote the range between the largest and lowest values from 8 snapshots. The annotated bars correspond to the sum of the values within the squares in figure 1 in the same color.

Transition of the KE budget between the resolved and dissipative regime The KE budget expressed as the vertical integration of equation (1) is depicted by the bars that correspond to the last four terms in the legend in figure 2. Note that steepening of the spectrum of the T159 resolution in figure 3 indicates an impact of resolution for $l > 30$. Indeed, we see a convergence of spectral energy exchange for T159 (right panel) for the group of wavenumbers between 41-60 (x-axis), which is virtually absent for the high resolution. KE generation (green with a black edge) is a factor two larger however, which indicates that these scales between 2.5-4 times the grid distance are partly resolved. The scales smaller than 2.5 grid distances are the dissipative regime, where KE is maintained mainly by the downscale cascade.

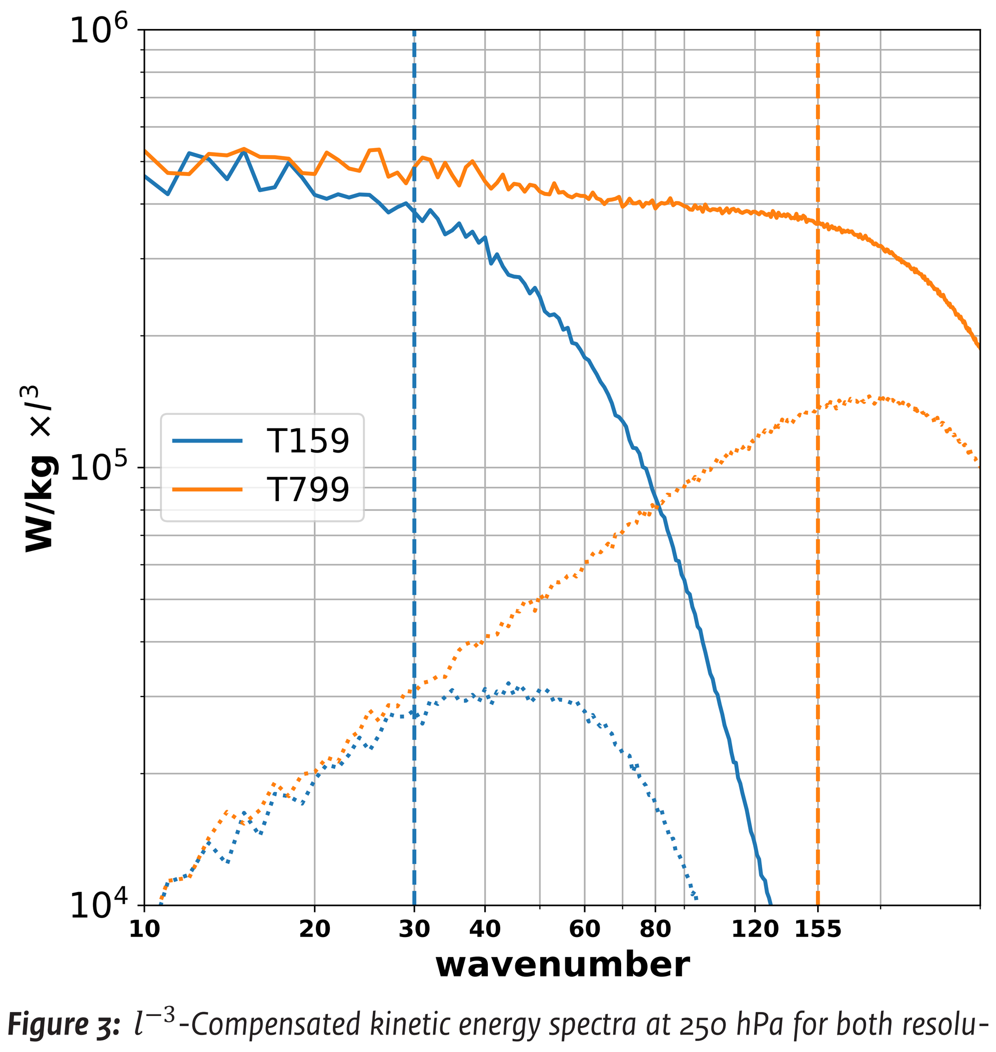

Figure 3: l^{-3}-Compensated kinetic energy spectra at 250 hPa for both resolutions, T159 (blue) and T799 (orange) in solid lines. Dotted lines denote the spectra derived from the divergent wind. The vertical dashed lines indicate the largest resolved wavenumbers (estimate based on the depicted spectra) for both resolutions in corresponding colors.

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