New findings on two fundamental issues in the atmospheric blocking dynamics: barotropic instability and upscale forcing

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Motivation:

It is well known that multiscale interaction plays a critical role in the atmospheric blocking dynamics, and has been the focus of numerous studies during the past few decades. However, a fully localized four-dimensional Lorenz energy cycle has not been obtained so far due to a lack of appropriate methodologies.

Two problems in conventional multiscale energetics formalisms and our solutions:

Problem 1: Multiscale energy is a phase-space notion; its localization is by no means trivial

If we have a signal with only two components $u(t) = \tilde{u}(t) + u'(t)$ — a low-frequency one $\tilde{u}(t) = a_0 cost$ and a high-frequency one $u'(t) = a_1 cos10t$, then what are the respective energies associated with them?

Empirical expression widely used in the literature	The fact we all know from the Fourier power spectrum
Energy for $\tilde{u}$: $(\tilde{u})^2$ Energy for u': $(u')^2$	Energy for $\tilde{u}$: a_0^2 Energy for u': a_1^2

Obviously, $(\tilde{u})^2 \neq a_0^2$, $(u')^2 \neq a_1^2$; in fact, they are conceptually different: $\tilde{u}(t)$ lies in physical space, while a_0^2 is in phase space!

Solution: In the above problem, the Fourier coefficients do not have the local information, which is usually needed for real atmospheric process studies. So the Fourier transform needs to be generalized, and this was the original motivation of those local transforms such as wavelets. For this particular problem, certain issues prevent wavelet transform from being directly applied, and Liang and Anderson (2007) hence developed Multiscale Window Transform (MWT) to handle the problem. While orthogonally making decomposition of a field by scale and providing filtered fields (reconstructions), MWT also provides transform coefficients for the corresponding filtered fields. This not only ensures energy conservation during a decomposition (thanks to the Parseval relation in functional analysis), but also makes it possible to express multiscale energies in terms of transform coefficients.

Problem 2: Separation of the cross-scale transfer process from the spatial transport process cannot be just performed arbitrarily; physical consistency must be enforced to have energy conserved

To demonstrate the problem, a Reynolds-decomposition is adopted here. For a scalar T advected by an incompressible flow **v**

$$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{v}T) = 0$$

Separate the fields into a mean part and a perturbation part. In this framework the equations of the mean and eddy energetics are, respectively,

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\bar{T}^2\right) + \nabla \cdot \left(\frac{1}{2}\bar{\mathbf{v}}\bar{T}^2\right) = -\bar{T}\nabla \cdot \left(\overline{\mathbf{v}'T'}\right), \quad (1)$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\overline{T'^2}\right) + \nabla \cdot \left(\frac{1}{2}\overline{\mathbf{v}T'^2}\right) = -\overline{\mathbf{v}'T'} \cdot \nabla \bar{T}. \quad (2)$$

where the two terms at the right hand side of Eqns. (1) and (2) are extensively interpreted as transfer term among scales. However, it is obvious that $-\bar{T}\nabla \cdot \left(\overline{\mathbf{v}'T'}\right) + (-\overline{\mathbf{v}'T'} \cdot \nabla \bar{T}) \neq 0$ This means that the energy transferred from the mean flow to eddies does not equals to the energy reserved by the eddies from the mean flow—**violating the principle of energy conservation**. This is caused by the fact that the empirical transport-transfer separation in Eqns. (1) and (2) is not unique and hence the resulting transfer is actually ambiguous (Holopainen 1978, Plumb 1983).

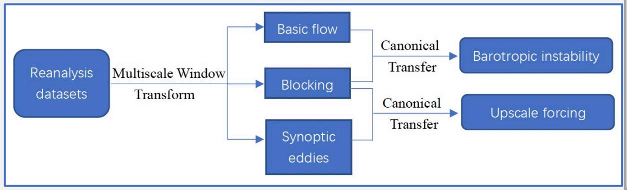
Solution: Liang (2016) demonstrated that the cross-scale energy transfer can be rigorously derived, and hence a unique separation of it from the multiscale transport is achieved naturally. In the special case with respect to Reynolds decomposition, the equations corresponding to (1) and (2) prove to be

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\overline{T'^2}\right) + \nabla \cdot \left(\frac{1}{2}\overline{\mathbf{v}T'^2} + \frac{1}{2}\bar{T}\overline{\mathbf{v}'T'}\right) = \Gamma. \quad (3)$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\bar{T}^2\right) + \nabla \cdot \left(\frac{1}{2}\bar{\mathbf{v}}\bar{T}^2 + \frac{1}{2}\bar{T}\overline{\mathbf{v}'T'}\right) = -\Gamma, \quad (4)$$

where $\Gamma = \frac{1}{2}\left[\bar{T}\nabla \cdot \left(\overline{\mathbf{v}'T'}\right) - \overline{\mathbf{v}'T'} \cdot \nabla \bar{T}\right]$. It is obvious that the right-hand terms now precisely add to zero. The resulting transfer $\Gamma = \frac{1}{2}\left[\bar{T}\nabla \cdot \left(\overline{\mathbf{v}'T'}\right) - \overline{\mathbf{v}'T'} \cdot \nabla \bar{T}\right]$. has a Lie bracket form, reminiscent of the Poisson bracket in Hamiltonian dynamics, and is hence termed as "canonical transfer" (see Liang, 2016).

Flow chart of this study



Reference:
Jiwang Ma, X. San Liang, 2023: Upstream–Downstream Asymmetry in Multiscale Interaction Underlying the Northern Hemisphere Atmospheric Blockings. Journal of the Atmospheric Sciences, 80, 1995–2011.

Result 1: Different from the famous eddy strain mechanism, the upscale forcing is found to dominate downstream, NOT upstream

For the interaction between the blocking and the high-frequency storms, the well-known critical role of the upscale forcing in the blocking development is confirmed. But, unexpectedly, except for that over the Atlantic where the forcing exists throughout, over the other two regions the forcing is found to occur mainly in downstream (Fig. 1). This is quite different from what the classical theory, e.g., the famous eddy strain mechanism of Shutts (1983), would predict (Fig. 2).

Fig.1

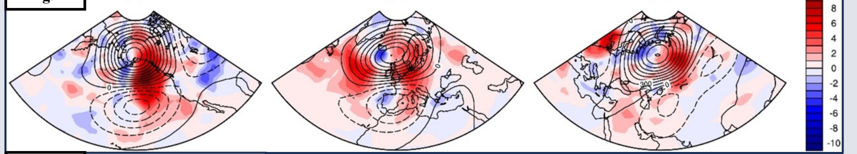


Fig.2

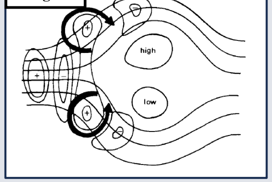


Fig. 1 Maps of upscale forcing from synoptic eddies to the (a) Pacific, (b) Atlantic, (c) Ural blockings (shaded; in $10^{-4} m^2 s^{-3}$). Contours are reconstructed geopotential (in m^2/s^2) on the blocking scale window.

Fig. 2 Schematic diagram of the Eddy Straining Mechanism (Shutts, 1983), in which the upscale forcing exerts on the upstream of the blocking.

Result 2:

Different from the traditional point of view, barotropic instability is found to be crucial

Thanks to the localized nature of the new methodology as used in this study, for the first time we identify a dipolar structure (for each of the three regions) in the map of the interscale energy transfer from the basic flow to the composite blocking, with a positive center upstream and a negative center downstream. This indicates the crucial role of the instability of the basic flow in maintaining the blocking, which **has been overlooked due to the bulk nature of the classical spatially integrated energetics**—By summing the transfer over the whole blocking, the two centers essentially cancel out, leaving an insignificant bulk transfer.

Fig.3

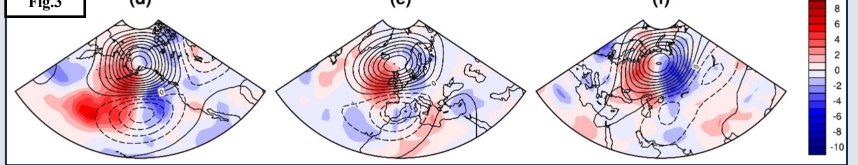


Fig. 3 Map of barotropic instability (shaded; in $10^{-4} m^2 s^{-3}$) underlying the (d) Pacific, (e) Atlantic, (f) Ural blockings. Contours are reconstructed geopotential (in m^2/s^2) on the blocking scale window.