Influence of Stratospheric Potential Vorticity on Baroclinic Lifecycles

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Abstract

The aim of this work is to investigate the dynamical coupling between the stratosphere and the troposphere. We consider the effect of perturbations to stratospheric potential vorticity on the evolution of baroclinic instability in the troposphere in simple lifecycle experiments. Both axisymmetric and non-axisymmetric perturbations are examined.

Model

The numerical model used is the Contour Advective Semi-Lagrangian (CASL) algorithm developed originally by Dritschel and Ambaum (1997) and extended to **cylindrical geometry** by Macaskill et al. (2003). The model is a representation of the main dynamics on a polar f-plane.

$$\frac{\mathrm{D}q}{\mathrm{D}t} = \frac{\partial q}{\partial t} + \boldsymbol{u}\cdot\nabla q = 0 \qquad (1)$$

Quasi-geostrophic framework:

- dominant balance in the atmosphere (large-scale, low-frequency motions)
- filters out small scales *e.g.* gravity waves
- layerwise 2D

$$q = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\psi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\theta^2} + \frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\frac{f^2}{N^2}\frac{\partial\psi}{\partial z}\right) \qquad (2)$$

$$\boldsymbol{u} = \left(-\frac{1}{r}\frac{\partial\psi}{\partial\theta}, \frac{\partial\psi}{\partial r}\right) \qquad (3)$$

where $q(r,\theta,z,t)$ is the (anomalous) PV, ψ is the geostrophic streamfunction, $\boldsymbol{u}=(u,v)$ is the horizontal geostrophic velocity and ρ_0 is the basic state density.

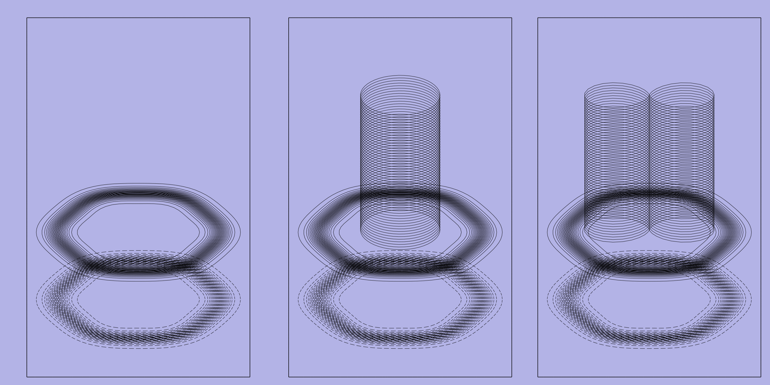
Potential Vorticity

Troposphere

- **interior:** assume uniform interior PV (Eady-type model).
- **surface:** surface temperature θ_s can be considered as a sheet distribution of PV.
- **tropopause:** jump in stratification leads to sheet-like distribution of PV at the tropopause, θ_t.

Stratosphere

- PV dominated by the polar vortex, represented by a volume of uniform PV.



PV contours of the 3 cases considered

Therefore the **total PV** is expressed by

$$q = \theta_t\delta(z - H_t) + \theta_s\delta(z) + q_{\mathrm{strat}}$$

The latitudinal dependence of θ_s and θ_t is given by

$$\theta_{s,t} = \Delta\theta_{s,t}\tanh(r/R)$$

where $R = L_R/2$ and where L_R is the deformation radius. $\Delta\theta_{s,t}$ represents (half) the pole-equator temperature difference.

The stratospheric PV is defined by

$$q_{\mathrm{strat}}(r,\theta,z) = \begin{cases} q_{\mathrm{in}} & \text{if } r < r_0(\theta,z) \\ q_{\mathrm{out}} & \text{if } r > r_0(\theta,z) \end{cases}$$

where $r_0(\theta,z)$ represents the location of the vortex edge (which may depend on longitude).

Results

The extreme case in which the stratospheric potential vorticity is exactly zero is used as a **control**. We then consider the effect of perturbations to the stratospheric potential vorticity that may be zonal (a crude representation of a strong vortex) or highly asymmetric (a crude representation of a vortex following a stratospheric sudden warming). Although the background tropospheric winds may change as a result of the stratospheric perturbations, changes to the vertical shear near the tropospheric jet are small. Both types of stratospheric perturbation result in dramatic changes to the baroclinic development of the control case.

Time evolution: The PV field is shown below for the 3 different cases at days 10, 12 and 14.

(1) Control

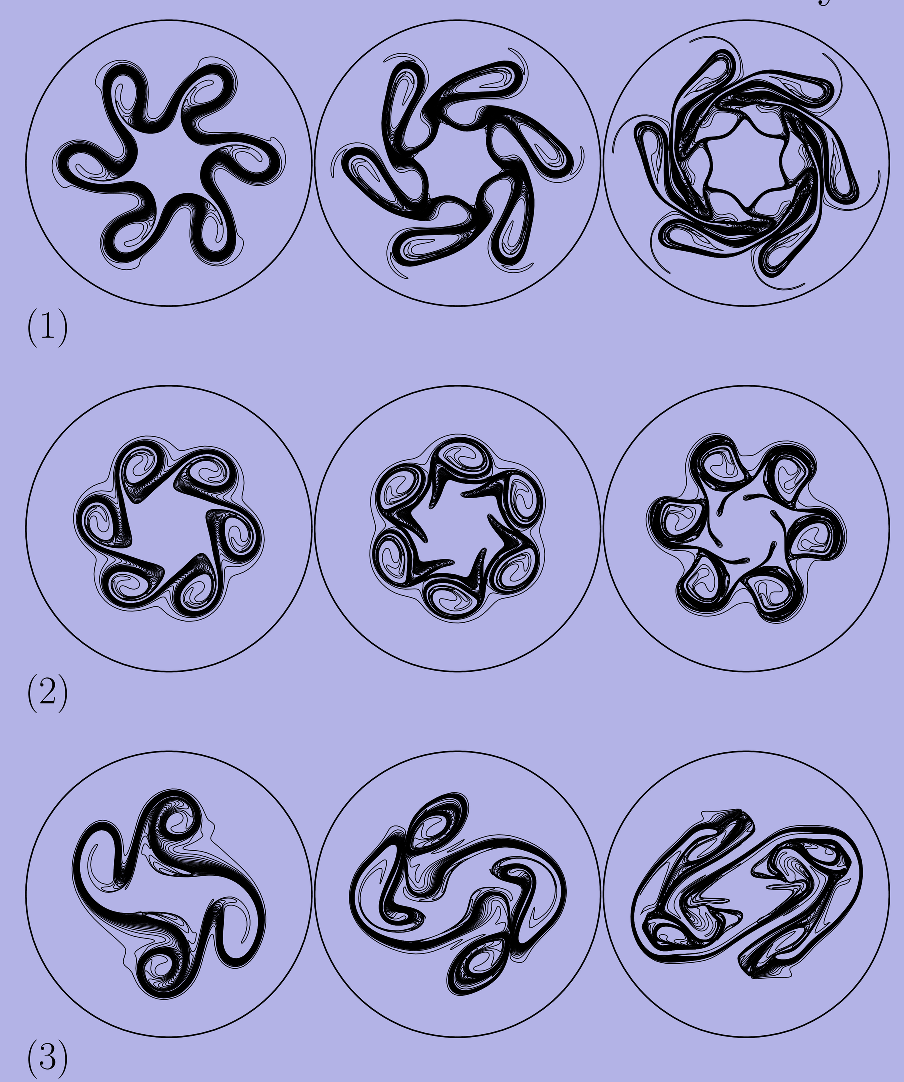
- two way breaking is observed

(2) Axisymmetric Perturbation

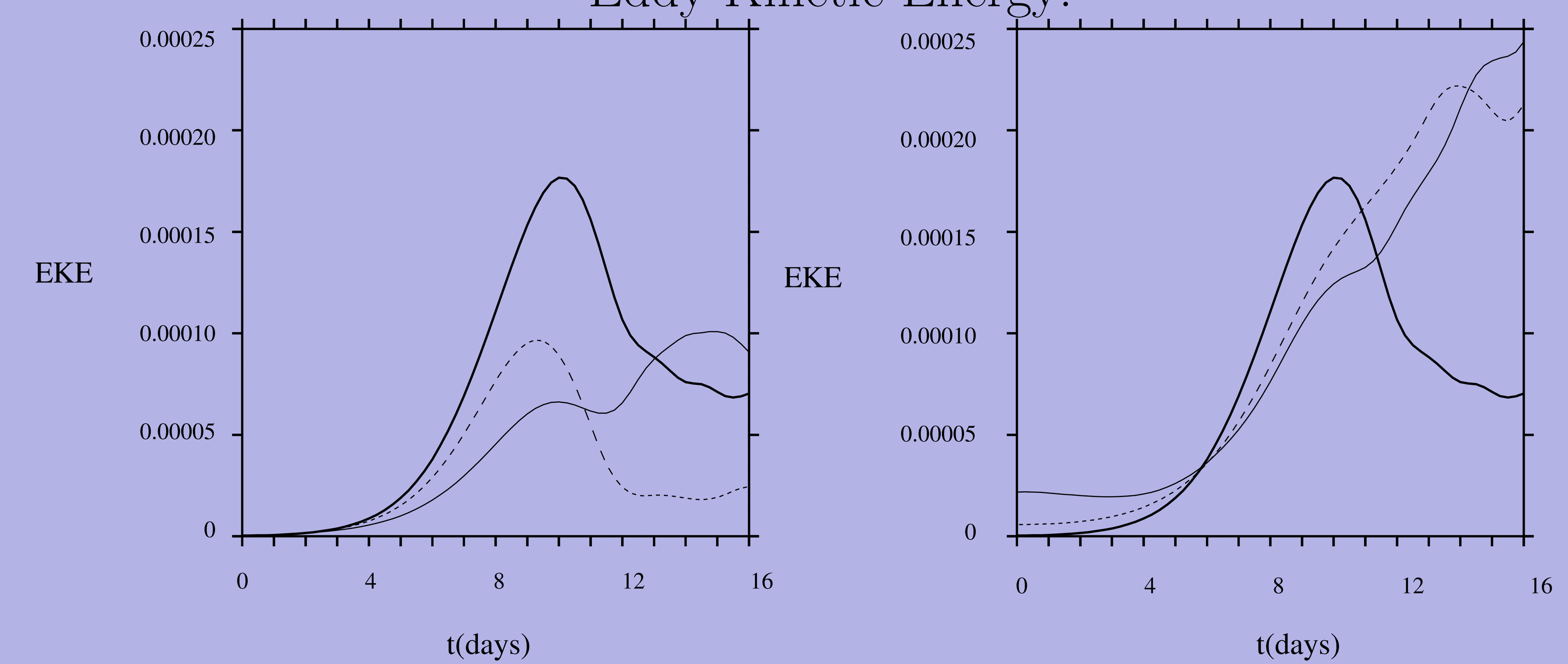
- one way breaking observed

(3) Split Vortex

- wave-2 dominates evolution



Eddy Kinetic Energy:



Axisymmetric Case

Split Vortex Case

[bold line is zero stratospheric PV, long-dashed is $\Delta Q = 0.2f$ and thin solid is $\Delta Q = 0.4f$]
(where $f = 2\Omega$)

The initial growth rate is reduced as the strength of the polar vortex increases. When there is an axisymmetric stratospheric PV perturbation the EKE maximum attained is reduced compared to the control case whereas with the split vortex, the wave-2 anomaly enables the EKE to reach greater values than the control case.

Conclusions

- We have found a strong dependence of Baroclinic Instability on the stratospheric PV or its rearrangement.
- This response is found in:
  - synoptic scale development
  - zonal and global means *e.g.* EKE, $\bar{u}$, geopotential
  - latitudinal heat transport
- The stratospheric PV anomalies considered affect a dipolar pattern of surface pressure that is qualitatively similar to the dominant variability of the troposphere (Arctic Oscillation). (See adjacent Figure)