Delineating the barotropic and baroclinic mechanisms in the midlatitude eddy-driven jet response to lower-tropospheric thermal forcing

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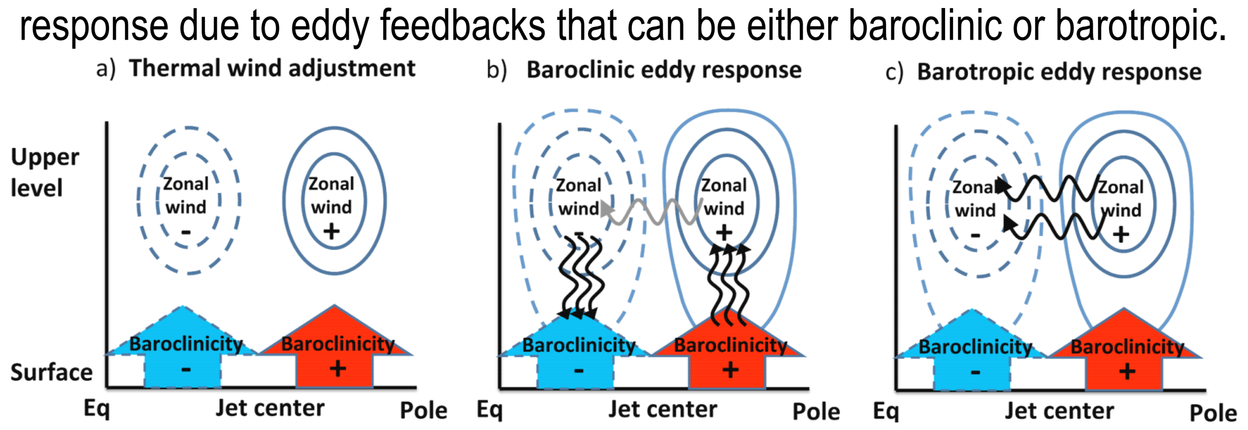
Introduction

• Observation and climate model simulations have shown that the eddy-driven jet exhibits evident latitudinal shift in response to the lower boundary thermal forcing, such as the El Nino-like warming, extratropical SST anomalies associated with the air-sea interaction, and the recent Arctic warming.

• The extratropical atmospheric circulation response to a lower-level thermal forcing can be understood as a direct thermal wind response plus an indirect response due to eddy feedbacks that can be either baroclinic or barotropic.



• In this study, the relative roles of baroclinic and barotropic mechanisms in the atmospheric response to thermal forcing are quantitatively compared.

Model description and Experiments Design

• A β plane multilevel quasi-geostrophic channel model is used. The model has a channel length of 21040 km, a channel width of 10000 km, and 17 equally spaced levels. Diabatic heating in this model is parameterized by the Newtonian cooling form.

• The jet shift in response to the lower-level thermal forcing are investigated through **systematically displacing the latitude of the lower level thermal forcing away from the channel center.**

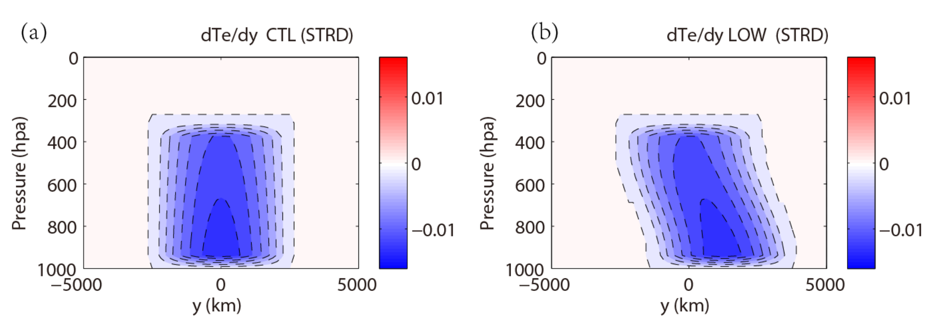


Fig 1: Profiles of the displaced zonal mean radiative convective temperature gradient in the (a) Control (CTL), (b) LOW runs.

Equilibrated Responses in the Standard LOW run

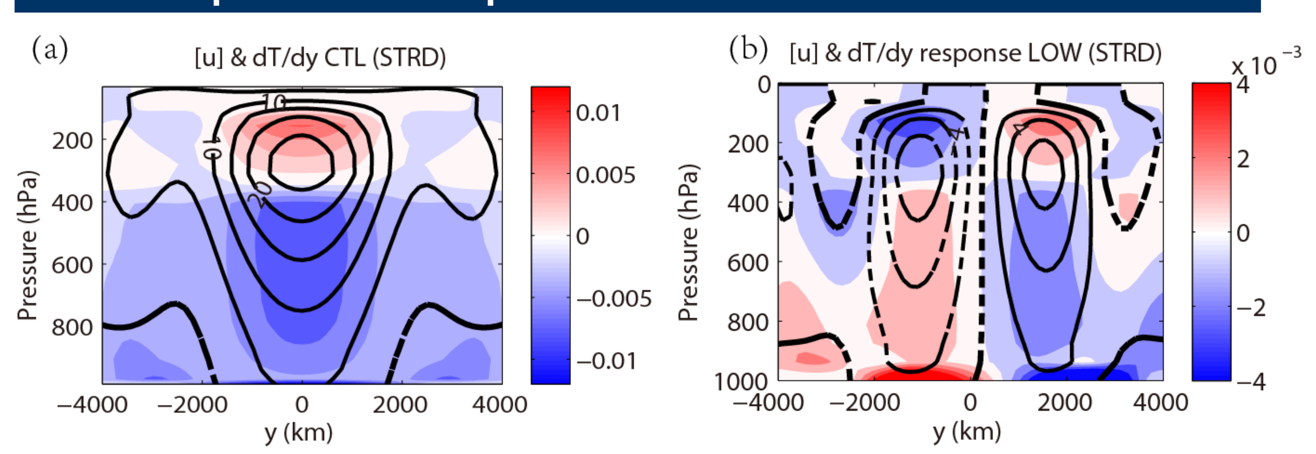


Fig 2: Profiles of (a) the equilibrated state zonal wind (contour) and temperature gradient (shading) in the standard CTL run and (b) equilibrated response in the standard LOW run.

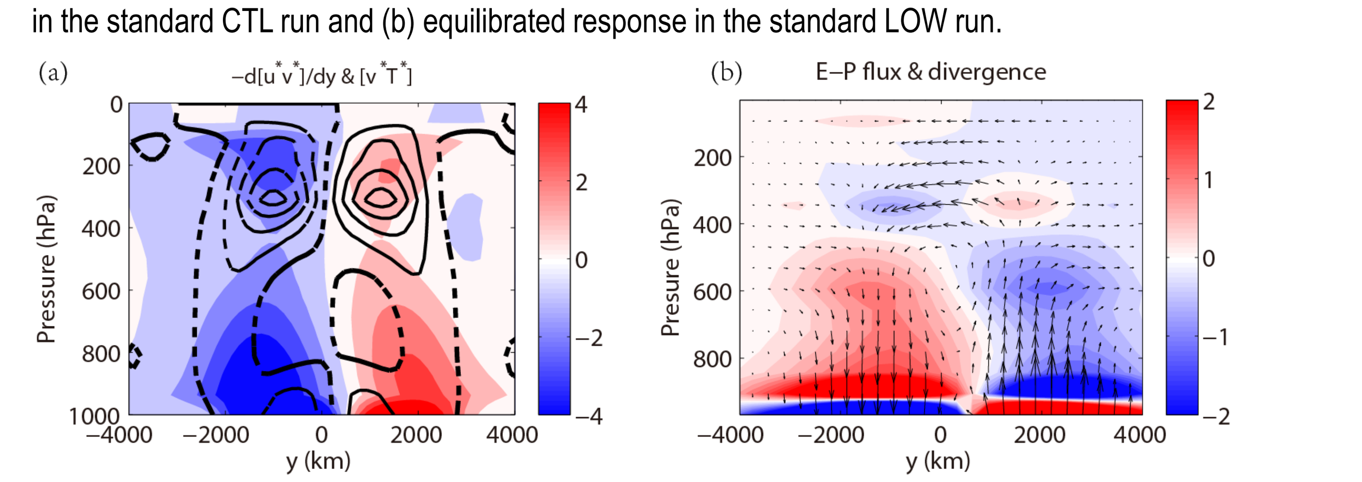


Fig 3: Equilibrated response of the eddy momentum flux convergence (contour) and eddy heat flux (shading), (b) equilibrated response of the E-P flux (vector) and E-P flux divergence (shading) in the standard LOW run.

• In response to the poleward shift of lower-level thermal forcing, the zonal wind, baroclinicity as well as the eddy statistics display **poleward displacement**.

Methodology: Finite Amplitude Wave Activity Analysis (FAWA)

$$-\frac{\partial[u^*v^*]}{\partial y}=-k_{eff}(Y_e,t)\frac{\partial Q(Y_e,t)}{\partial Y_e}-\frac{\partial}{\partial p}\left(\frac{f[v^*\theta^*]}{\partial\theta_s/\partial p}\right)-\frac{\partial A(Y_e)}{\partial t}+\Delta\Sigma$$

Barotropic process Baroclinic process

• Through the FAWA analysis, both the **barotropic and baroclinic** processes can be **quantitatively** compared.

Transient Response to the imposed thermal forcing

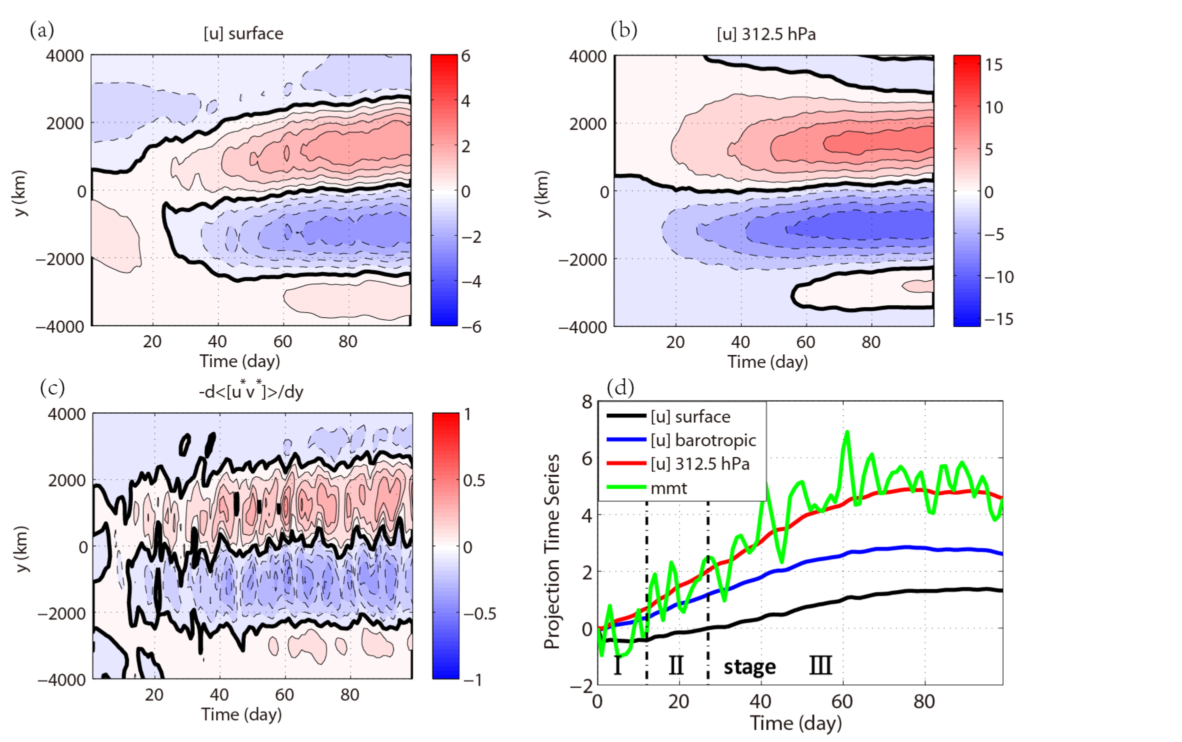


Fig 4: The time evolutions of anomalous (a) surface zonal wind, (b) zonal wind at 312.5 hPa and (c) vertically averaged eddy momentum flux convergence in the transient experiment. (d) The projections of the zonal winds and eddy momentum flux convergence onto the equilibrated response pattern of the surface zonal wind in the standard LOW run.

Stage I (days 1-12): The surface zonal wind shifts equatorward but upper tropospheric zonal wind shifts poleward. The eddy response is weak.

Stage II (days 13-27): The surface zonal wind is still at the equatorward side to its initial position, but it begins to move poleward. The eddy momentum flux convergence has a weak poleward shift.

Stage III (days 28-80): The upper and lower zonal winds show consistent poleward shift, with strong eddy response.

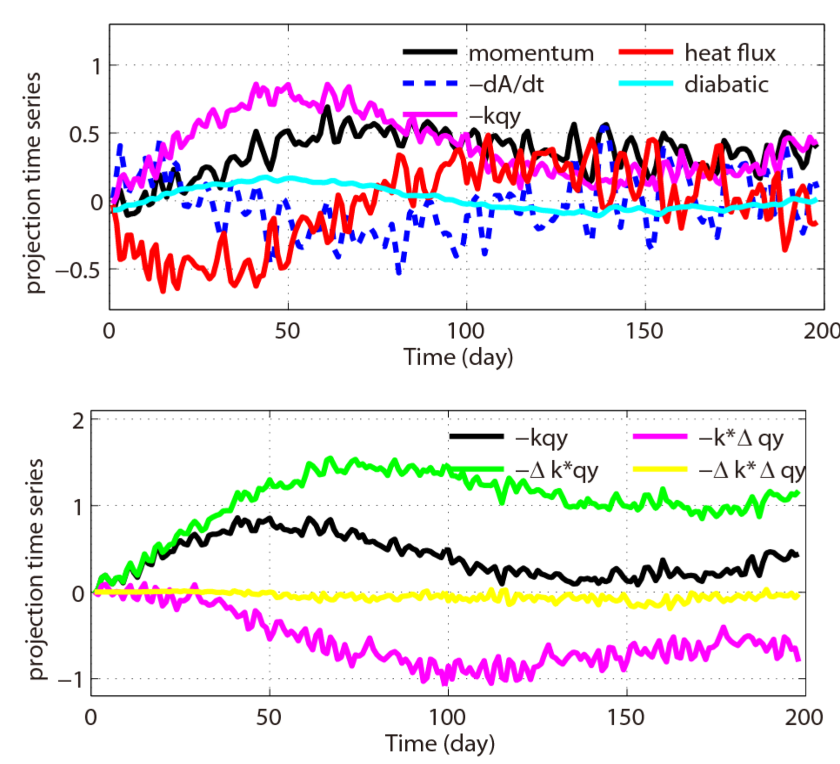


Fig 5: (a) Time series of each forcing term in the FAWA budget at 312.5 hPa. (b) is same as (a) but for each component in the barotropic term in the FAWA budget.

• **The barotropic and baroclinic eddy processes contribute differently** to the poleward shift of eddy momentum flux convergence.
• The **barotropic term plays a dominant role** in the poleward shift of eddy momentum flux convergence.
• The **baroclinic term exhibits a regime transition**.
• The positive contribution of barotropic processes is primarily due to the change in **effective diffusivity**.

Dynamical Mechanisms in the standard LOW run

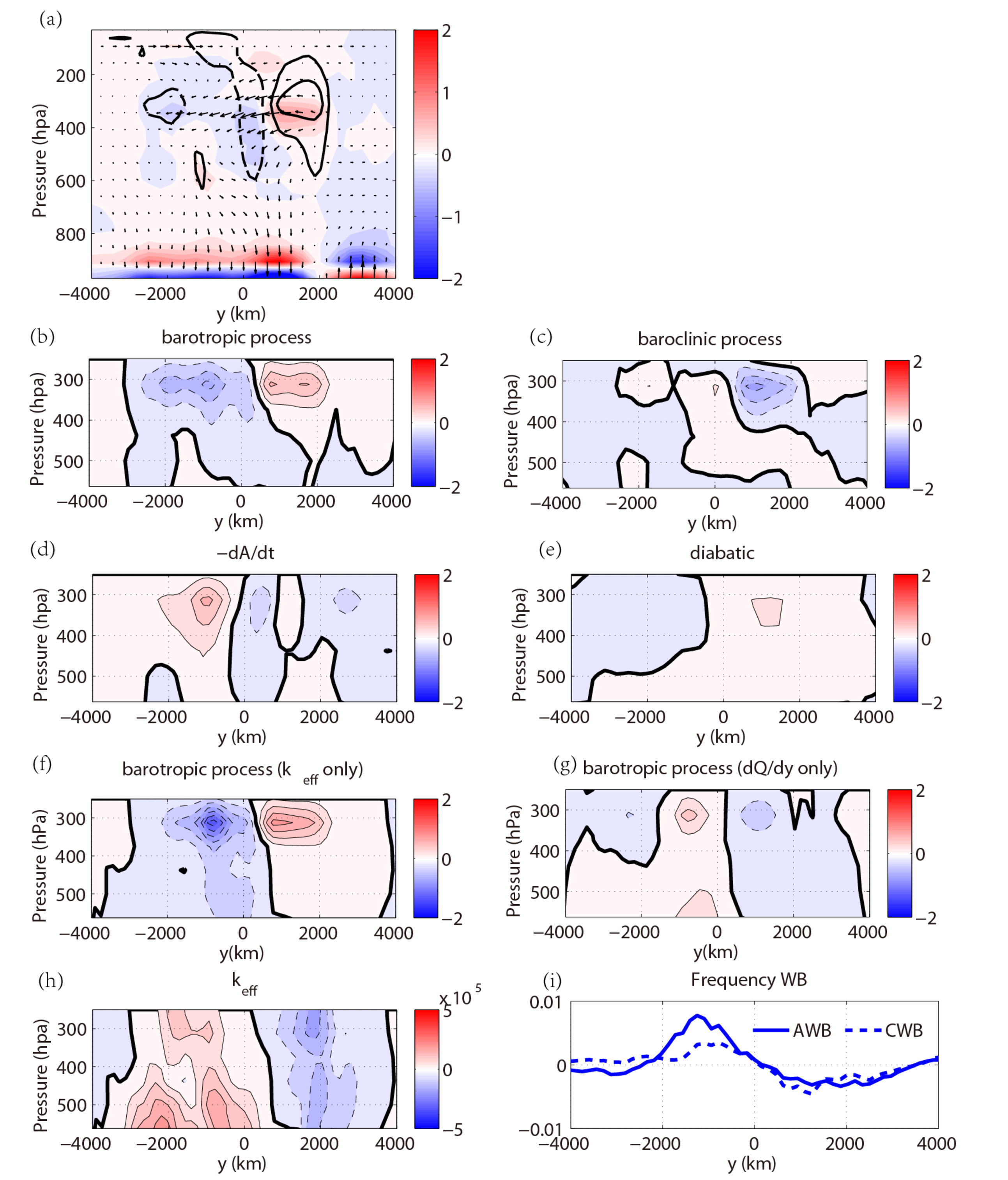
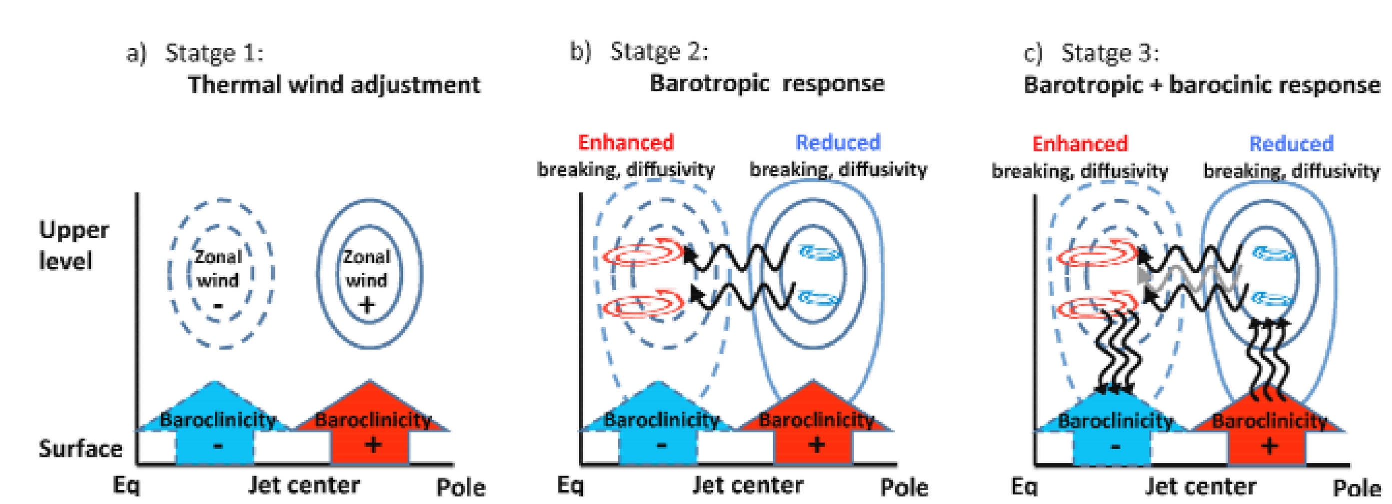


Fig 6: Zonal and ensemble-mean transient responses in E-P flux and FAWA budget during stage II. (a) The E-P flux (vector), E-P flux divergence (shading) and the eddy momentum flux convergence (contour), (b) barotropic process, (c) baroclinic process, (d) negative time tendency of wave activity, (e) diabatic heating, (f) barotropic process due to the change of the effective diffusivity, (g) barotropic process due to the change of the PV gradient, (h) effective diffusivity and (i) Rossby wave breaking frequency.

• The poleward shift of the eddy momentum forcing during stage II mainly results from the change of the **barotropic processes** in the upper troposphere.
• The change of the barotropic processes is primarily due to the change of the **effective diffusivity.**
• The effective diffusivity shows a reduction on the poleward side and an enhancement on the equatorward. This can be thought of as the result of a strong zonal jet in suppressing the effective diffusivity of PV mixing.

Schematics of the Key Dynamical Processes

The mechanism of the circulation response to the lower-level thermal forcing is summarized as below:



Overriding Experiments: Barotropic vs. Baroclinic Feedbacks

• **Baroclinic Response Run:** keep the baroclinic eddy feedback active but suppress the barotropic eddy feedback. In the experiment, the lower-level thermal forcing is kept the same as in the standard LOW run, but the barotropic zonal wind in the PV advection is fixed as the climatological mean in the standard CTL run.

• **Barotropic Response Run:** keep the barotropic eddy feedback but remove the baroclinic eddy feedback. In the experiment, the thermal forcing in the CTL run is used, while the climatological mean barotropic zonal wind in the standard LOW run is remained in the PV advection.

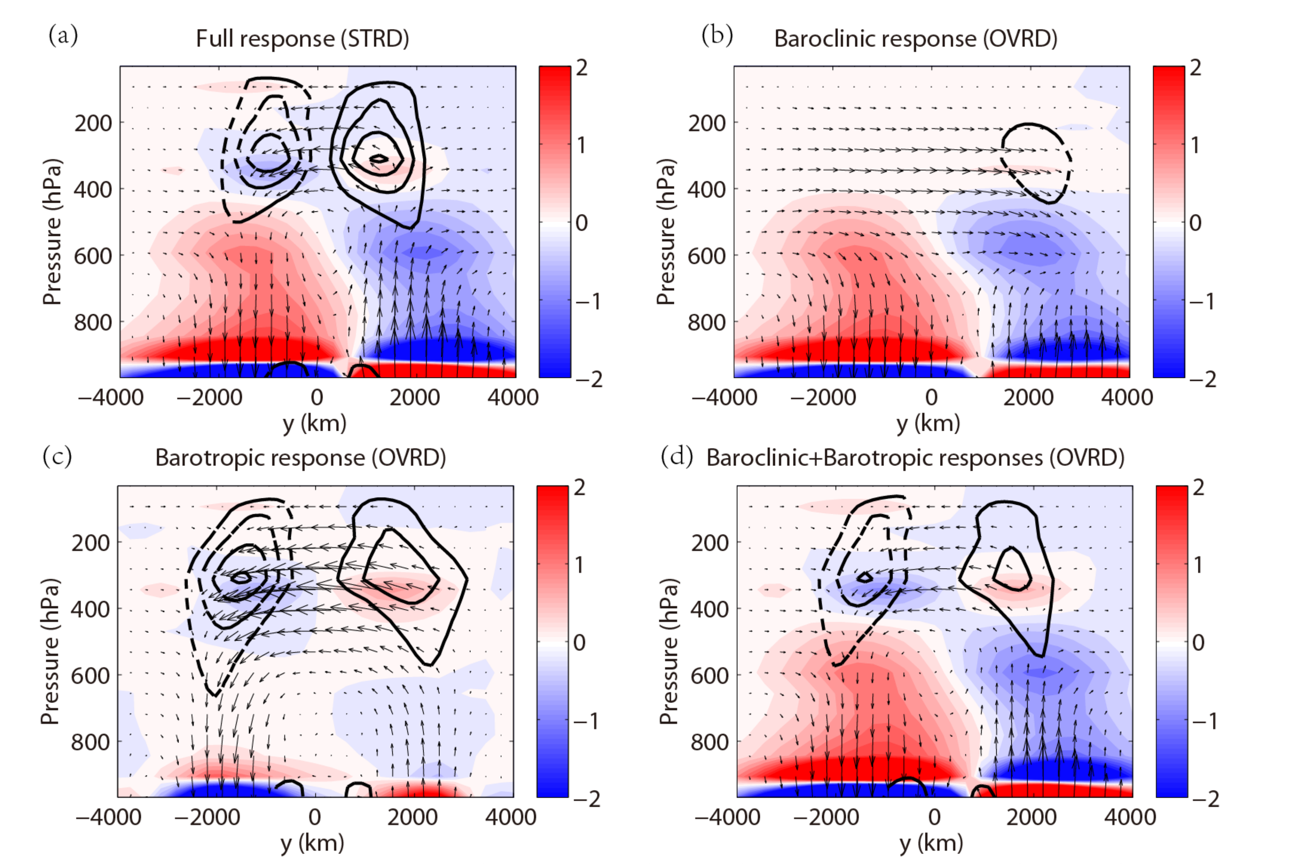


Fig 4: Equilibrated response of the E-P flux (vectors), E-P flux divergence (shading) and eddy momentum flux convergence (black contour) for (a) standard LOW run, (b) baroclinic response run, (c) barotropic response run and (d) barotropic plus baroclinic response run.

• **The barotropic and baroclinic processes can be effectively separated by setting up the overriding experiments.**

• **The barotropic eddy response due to the change in barotropic zonal flow dominates** the total atmospheric response to the lower-level thermal forcing.

Conclusions

• Using a nonlinear β plane multi-level QG channel model, by diagnosing the FAWA budget, the baroclinic and barotropic eddy feedbacks in response to the lower-level thermal forcing are delineated.

• Through examining the transient circulation response after the thermal forcing is switched on, it is shown that **the lower-level thermal forcing affects the eddy-driven jet rapidly by modifying the upper-level zonal thermal wind distribution and the associated meridional wave propagation and breaking**. The anomalous baroclinic eddy generation, however, acts to enhance the latitudinal shift of the eddy-driven jet only in the later stage of transient response.

• The barotropic mechanism is explicated through the overriding experiments in which the barotropic flow in the vorticity advection is prescribed.

• Unlike the conventional baroclinic view, our study shows that the barotropic eddy feedback, particularly the irreversible PV mixing through barotropic vorticity advection and deformation, plays a major role in the atmospheric circulation response to the lower-level thermal forcing.