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Effects of the Tibetan Plateau on East Asian Summer Monsoon via Weakened Transient Eddies

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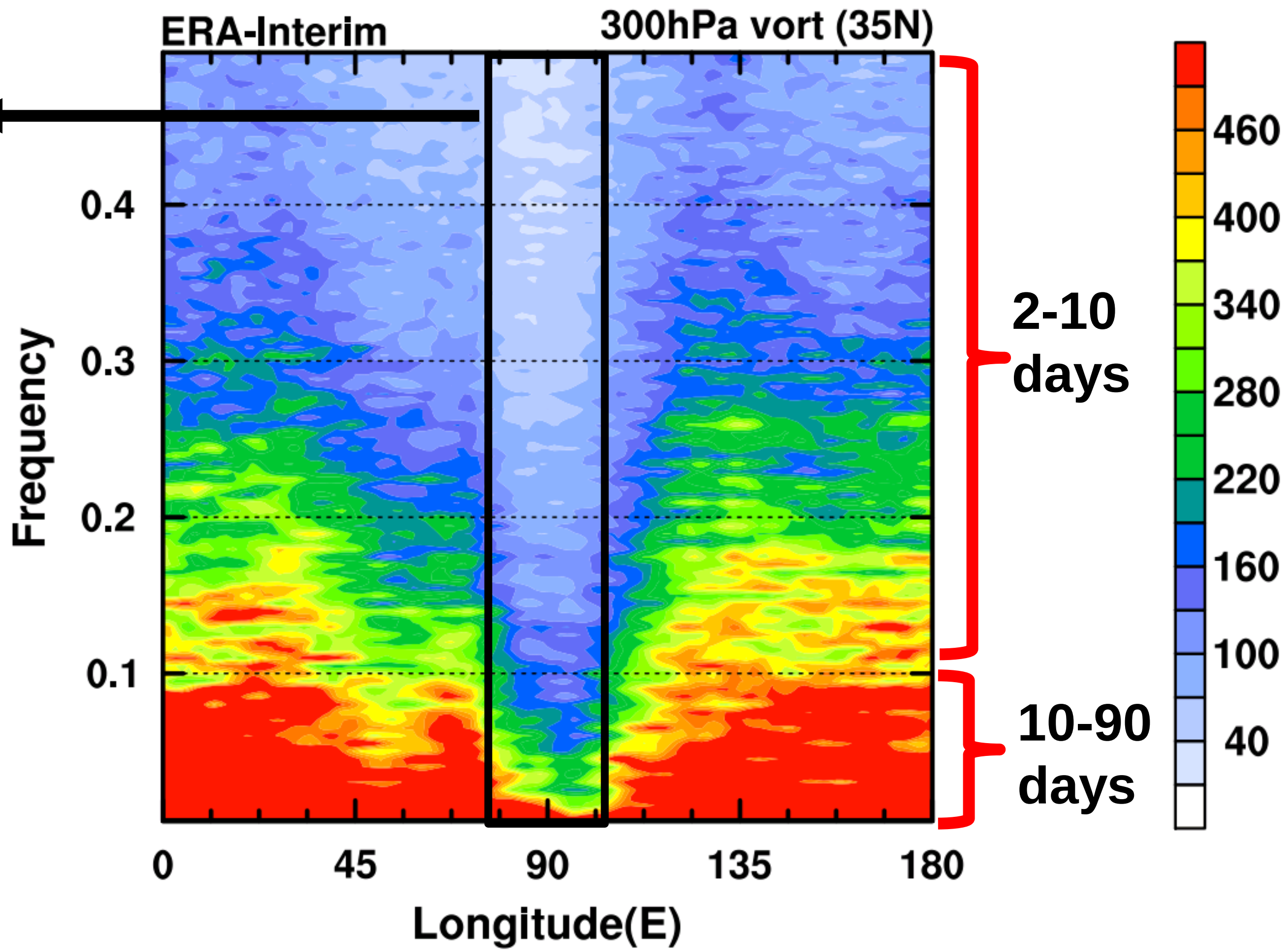
1. Introduction

Tibetan Plateau (TP) can weaken the high-frequency and low-frequency transient eddies (TEs) transported from upstream to downstream.

Yu and Hartmann 1995;
Chang et al. 2002;
Son et al. 2009;
Park et al. 2010, 2013;
Lee et al. 2013



Power Spectrum of the 300hPa relative vorticity as a function of longitude and frequency which follows the study of Yu (1995). The powers are calculated from daily ERA-interim reanalysis data and are averaged over 50 adjacent frequency bands. (units: $10^{-4}s^{-2}$)

1. Introduction

The importance of TE:

- **TE plays an important role in the atmospheric transportation of energy (kinetic energy, heat) and matter (water vapor).**
- **TE can influence general circulation through wave-mean flow interaction.**

The importance of TP:

- **The thermal forcing of TP is a major driver of moisture transport from tropical oceans to northern India and east China.**
- **The mechanical forcing of TP can deflect the air flow impinging upon TP to produce encircling flow or lift the air parcels to produce climbing flow.**

Scientific question：

How does the TP’s inhibition of TE affect the East Asian Summer Monsoon (EASM)?

1. Introduction

Two difficulties that lead to the less studies about this question.

- **Moist processes, the characteristic of EASM, complicate the wave-mean flow interaction by latent heat release. So the dry simple model which is usually used by previous studies to investigate the feedback between TE and time-mean flow cannot be used in this study.**

- **Distinguish the role of TP's inhibition of TE from the total climatic effects of TP including the steady dynamic and thermodynamic effects. The mostly used method, changing the height or topography of the TP in model, not only removes the TP's effects on TE but also changes the mechanical and thermal forcings of the TP which are essential to EASM.**

Innovation:

A grid nudging method is used in CESM to amplify the TP's inhibition of TE without changing the steady dynamic and thermal forcings of TP, so the differences between sensitivity experiment (NG6h) and control experiment (CTRL) are mainly driven by TP's inhibition of TE.

2. Methodology

Apply Grid Nudging in CESM

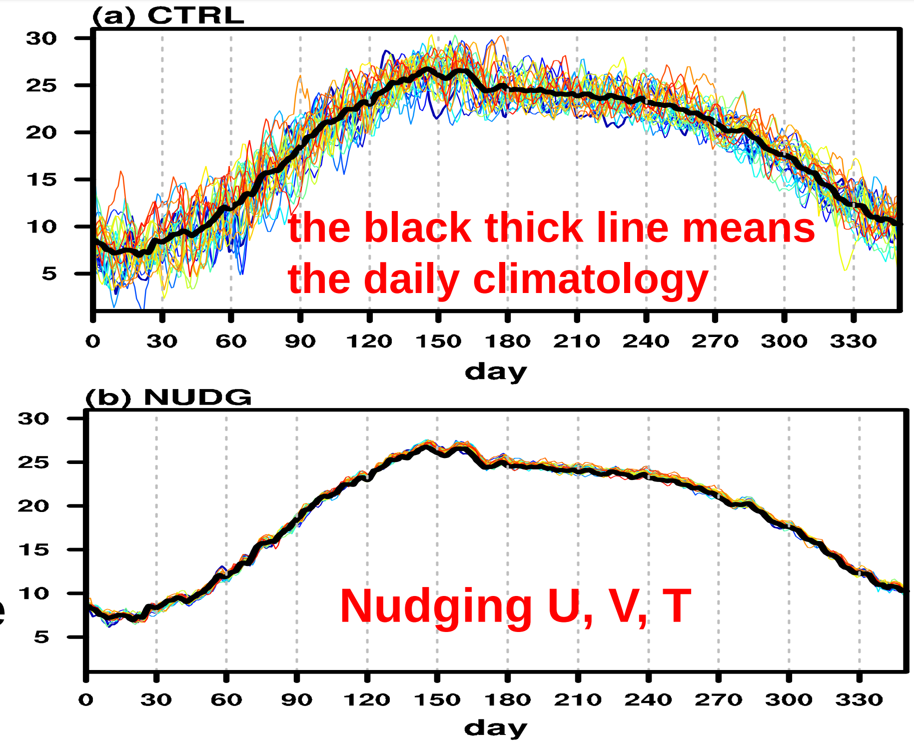
Target field

Model field

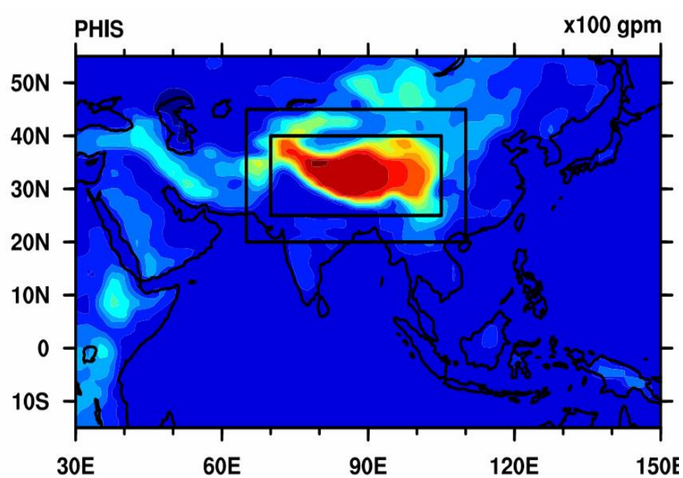
$$\frac{\partial A}{\partial t} = F + G_A W_A (A_{clim} - A)$$

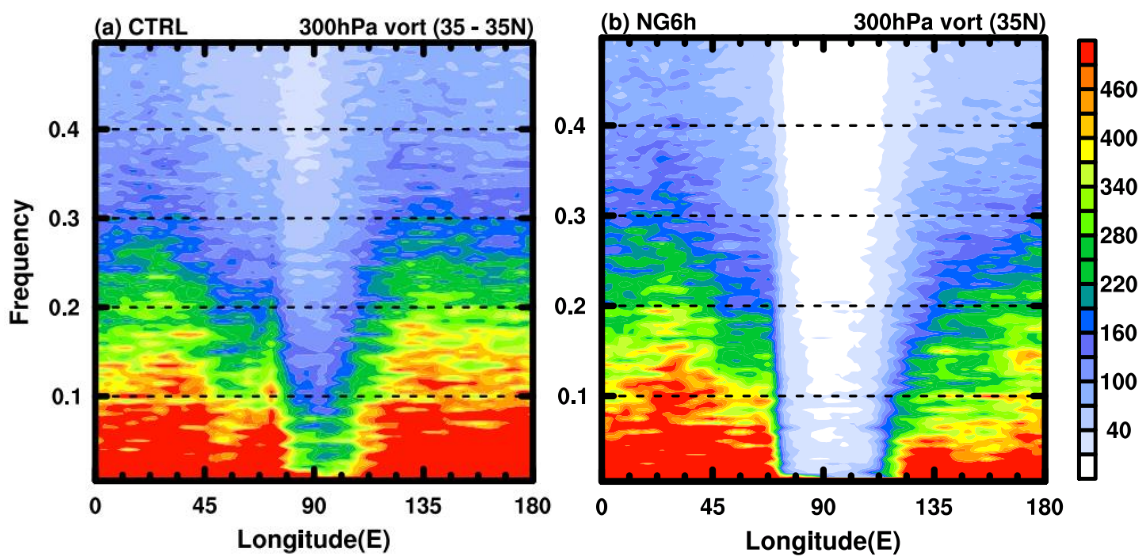
Physical forcing due to physical processes, advection, and Coriolis

Relaxation intensity factor, generally the reciprocal of slack time



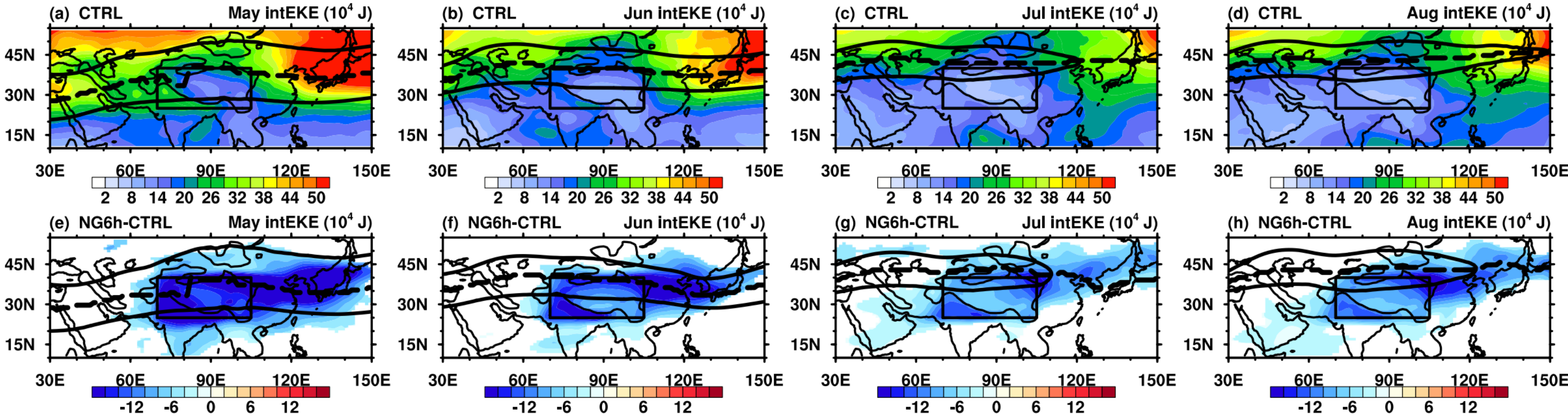
$1.25^\circ \times 0.9^\circ \quad (\mathrm{lon} \times lat)$





2. Methodology

Amplify the TP’s inhibition of TE



Vertically integrated climatic kinetic energy of TE in CTRL case (10^4J, shading) in (a) May, (b) June, (c) July and (d) August. Thick solid lines is the 20 m/s isotach of 200hPa zonal wind and the thick dashed line is the axis of the 200hPa westerly jet. (e)-(h) are the same as (a)-(d) but for the differences between NG6h and CTRL case in which only the values significantly exceeding the 95% confidence level are shown.

- **After amplifying the TP’s inhibition of TE, TP can further reduce the TE transported to East Asia and the degree of reduction depends on the meridional position of the westerly jet stream relative to the TP.**
- **Due to the similar effects of the suppressed TE by TP in May and June, and in July and August, summer is divided into early summer and late summer in the rest of the study.**

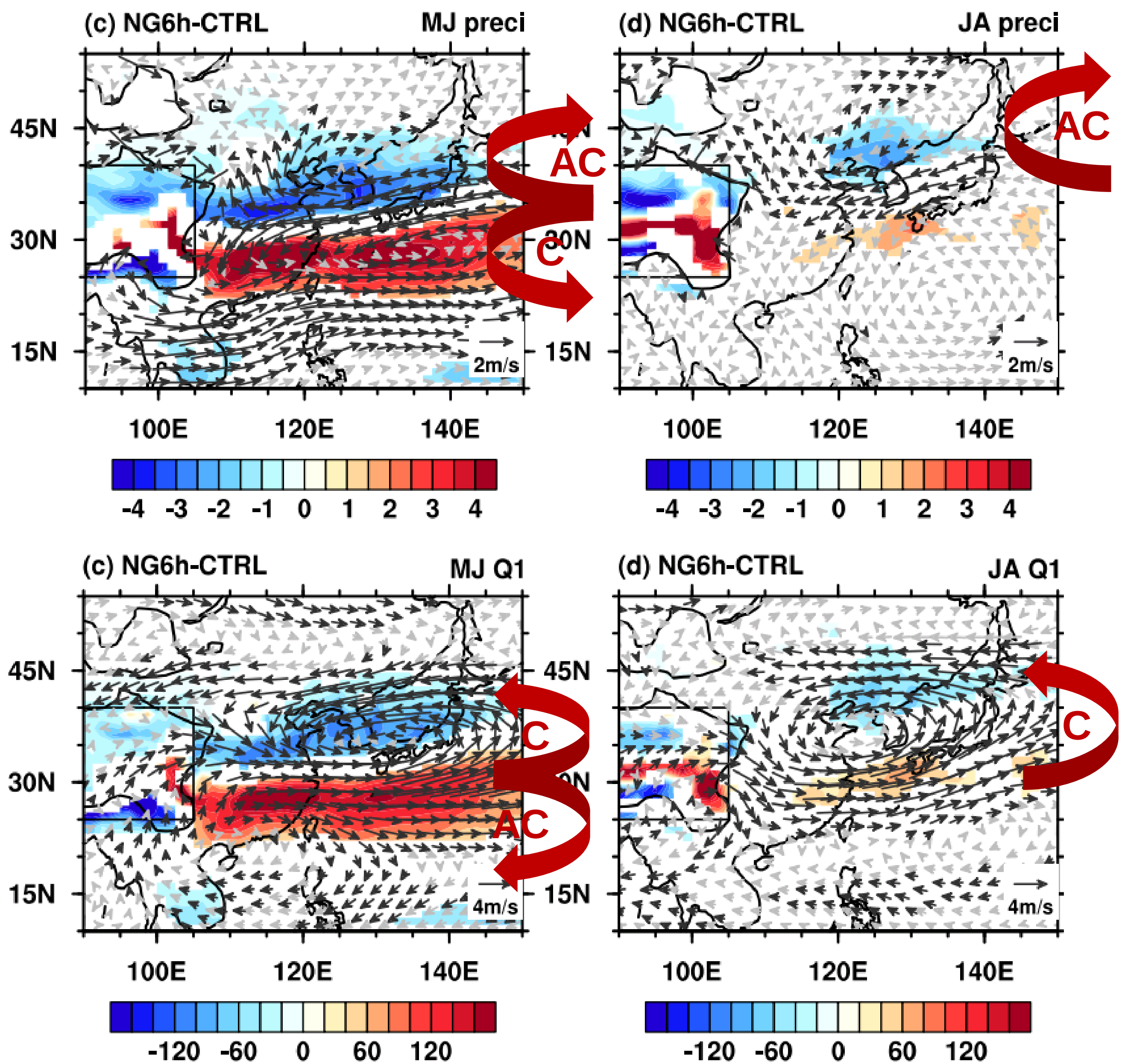
3. Transient Effects of TP on EASM

Early Summer

Late Summer

850hPa wind & rainfall

200hPa wind & Q1



4.1 Circulation diagnosis via geopotential tendency

Geopotential tendency equation which is derived from the quasi-geostrophic potential vorticity equation

$$\left\{\frac{1}{f}\nabla^2 + f\frac{\partial}{\partial p}\left(\frac{1}{\tilde{\bar{\sigma}}}\frac{\partial}{\partial p}\right)\right\}\frac{\partial\bar{\Phi}}{\partial t} = -fR\frac{\partial}{\partial p}\left(\frac{\overline{Q_d}}{\tilde{\bar{\sigma}}p}\right) - fR\frac{\partial}{\partial p}\left(\frac{\overline{Q_{te}}}{\tilde{\bar{\sigma}}p}\right) + \overline{F_{te}} + R_v$$

$$\frac{\partial u}{\partial t} = -\frac{1}{f}\frac{\partial}{\partial y}\left(\frac{\partial \Phi}{\partial t}\right)$$

Diabatic heating : $Q_d = \frac{\bar{u}}{a\cos\varphi}\frac{\partial\bar{T}}{\partial\lambda} + \frac{\bar{v}}{a}\frac{\partial\bar{T}}{\partial\varphi} - \bar{\sigma}_0\bar{\omega} - Q_{eddy}$

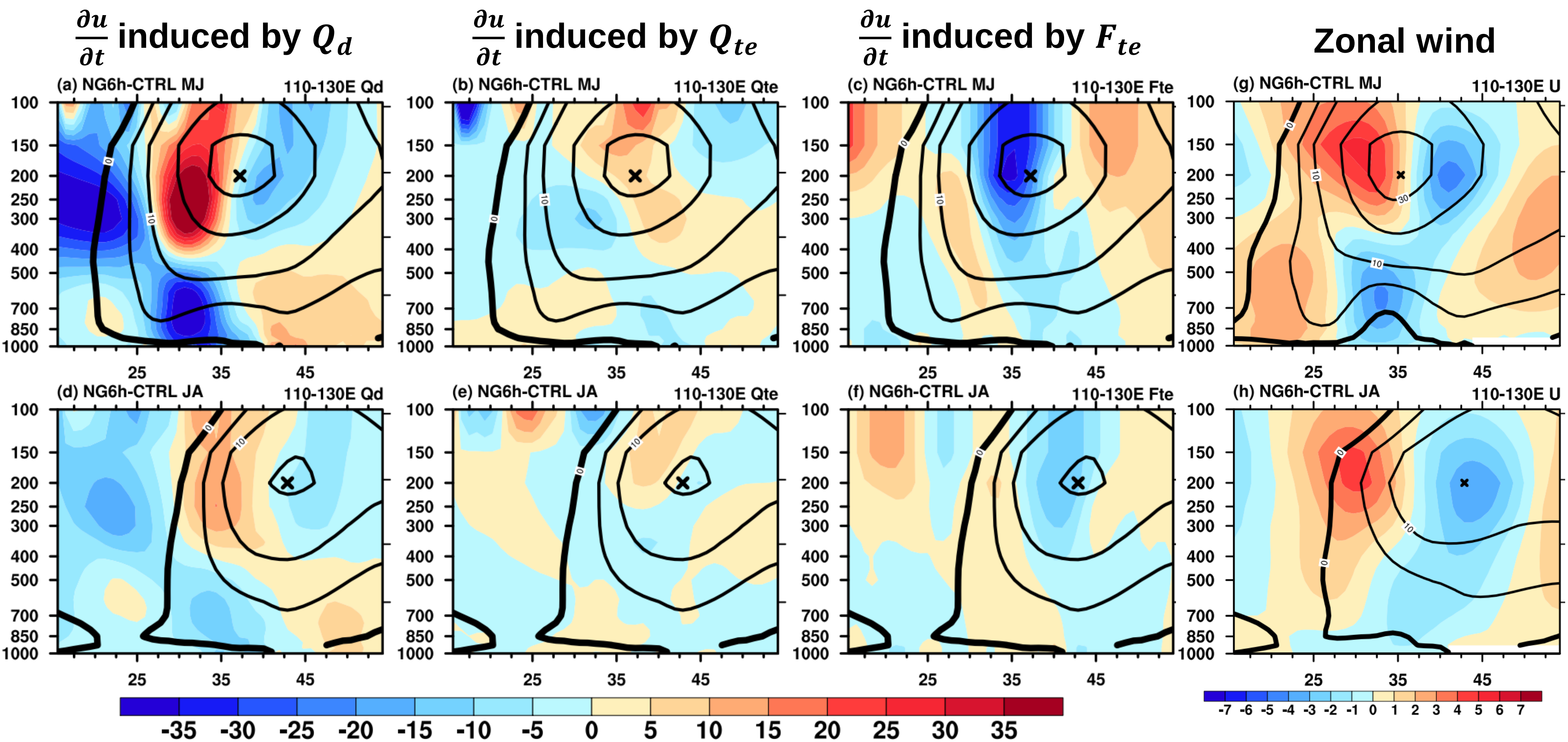
Transient eddy heating : $\overline{Q_{te}} = -\nabla\cdot\overline{\vec{V}_h'T'} - \frac{\partial\overline{\omega'T'}}{\partial p} + \frac{R}{c_p p}\overline{\omega'T'}$

Transient eddy vorticity forcing : $\overline{F_{te}} = -\nabla\cdot\overline{\vec{V}_h'\zeta'}$

R_v **is considered to be a residual term including the horizontal advection of quasi-geostrophic potential vorticity and the friction.**

(Lau and Holopainen, 1984)

4.1 Circulation diagnosis via geopotential tendency



Black contours represent the climatological westerly wind in CTRL.

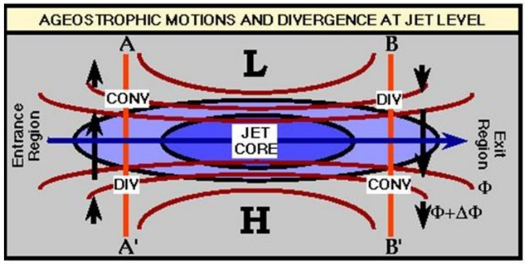
Black contours represent the westerly wind in NG6h.

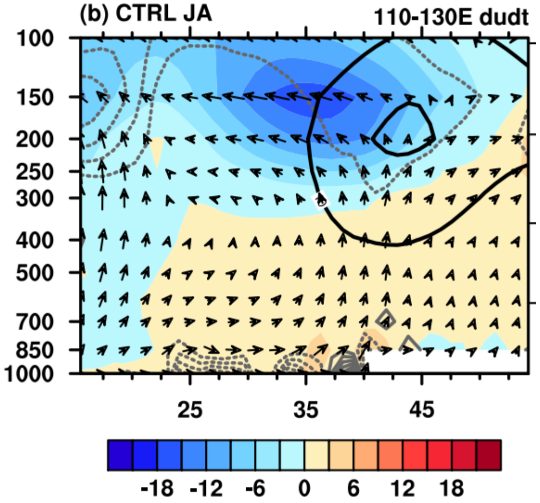
- **The baroclinic anomalous zonal wind in early summer are mainly induced by the anomalous strong diabatic heating.**
- **The barotropic anomalies in late summer are mainly caused by the anomalous TE vorticity forcing.**

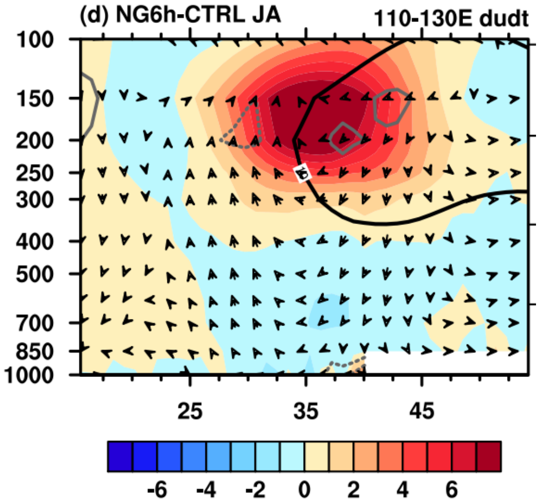
4.2 Physical processes of precipitation changes

The secondary circulation of the westerly jet stream

$$v_g = \frac{1}{f}\frac{\partial \emptyset}{\partial x} \Rightarrow \frac{du}{dt} = f(v - v_g)$$







Shading: material derivative of zonal wind ($10^{-5} m/s^2$)

Gray contours: horizontal divergence, solid (dashed) denote convergence (divergence)

Vector: meridional circulation

Black contours: westerly wind (contour interval: 10m/s)

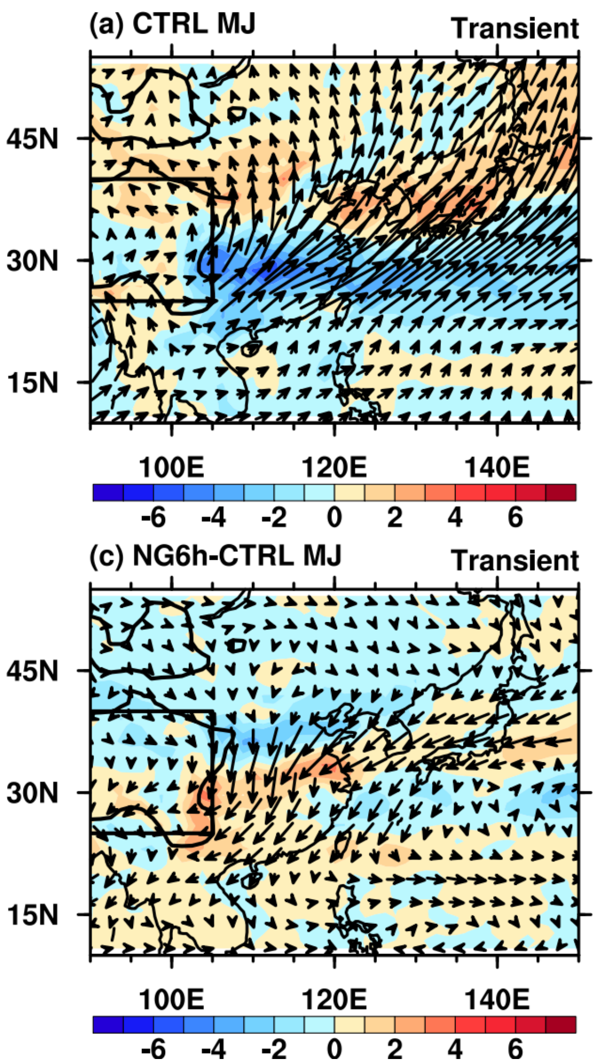
- **The anomalous barotropic circulation resulted from the suppressed poleward TE vorticity in late summer weaken the upper-level westerly deceleration, producing the south-divergent-north-convergent anomalies at the upper level.**
- **Since the activity of TE over TP is suppressed all the time in NG6h, these divergent anomalies always exist, conducive to the equatorward movement of the East Asian rain belt**

4.2 Physical processes of precipitation changes

TE effects on moisture transport

$$\overline{\overline{qv}} = \overline{\overline{q}}\,\overline{\overline{v}} + \overline{\overline{q'v'}}$$

climate steady transient



Gradient transport theory

$$\overline{q'v'} \propto K\frac{\partial \overline{q}}{\partial y}$$

- **The meridional moisture gradient over East Asia is large in early summer, causing the strong poleward TE moisture fluxes.**
- **The TP's inhibition of TE weakens the poleward TE moisture fluxes, causing more water vapor to gather in southern East Asia, accompanying the anomalous divergent field at upper level favors the elongated dipole rainfall anomalies.**
- **The anomalous latent heat released by the rainfall anomalies generates the anomalous baroclinic circulations which promote the convergence of water vapor in southern East Asia and move the EAWJ southward, forming a positive feedback to further reinforce the precipitation anomalies.**

Vertically-integrated transient moisture transport and its divergence (shading; positive values denote convergence)

4.2 Physical processes of precipitation changes

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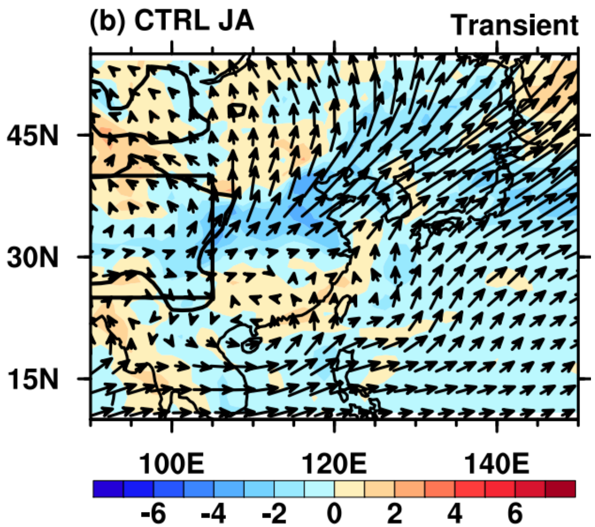
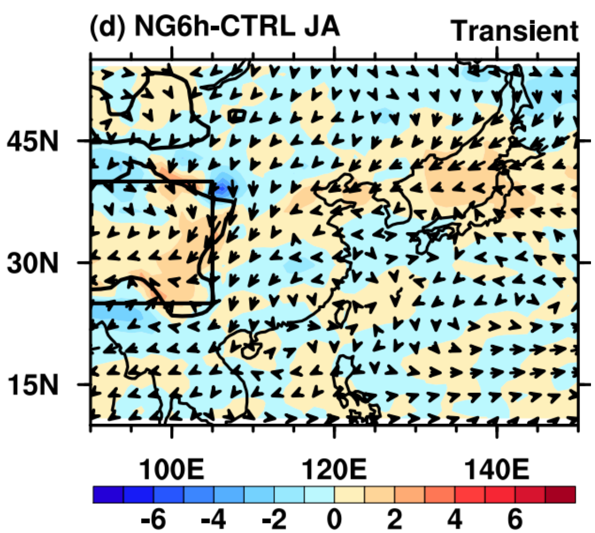




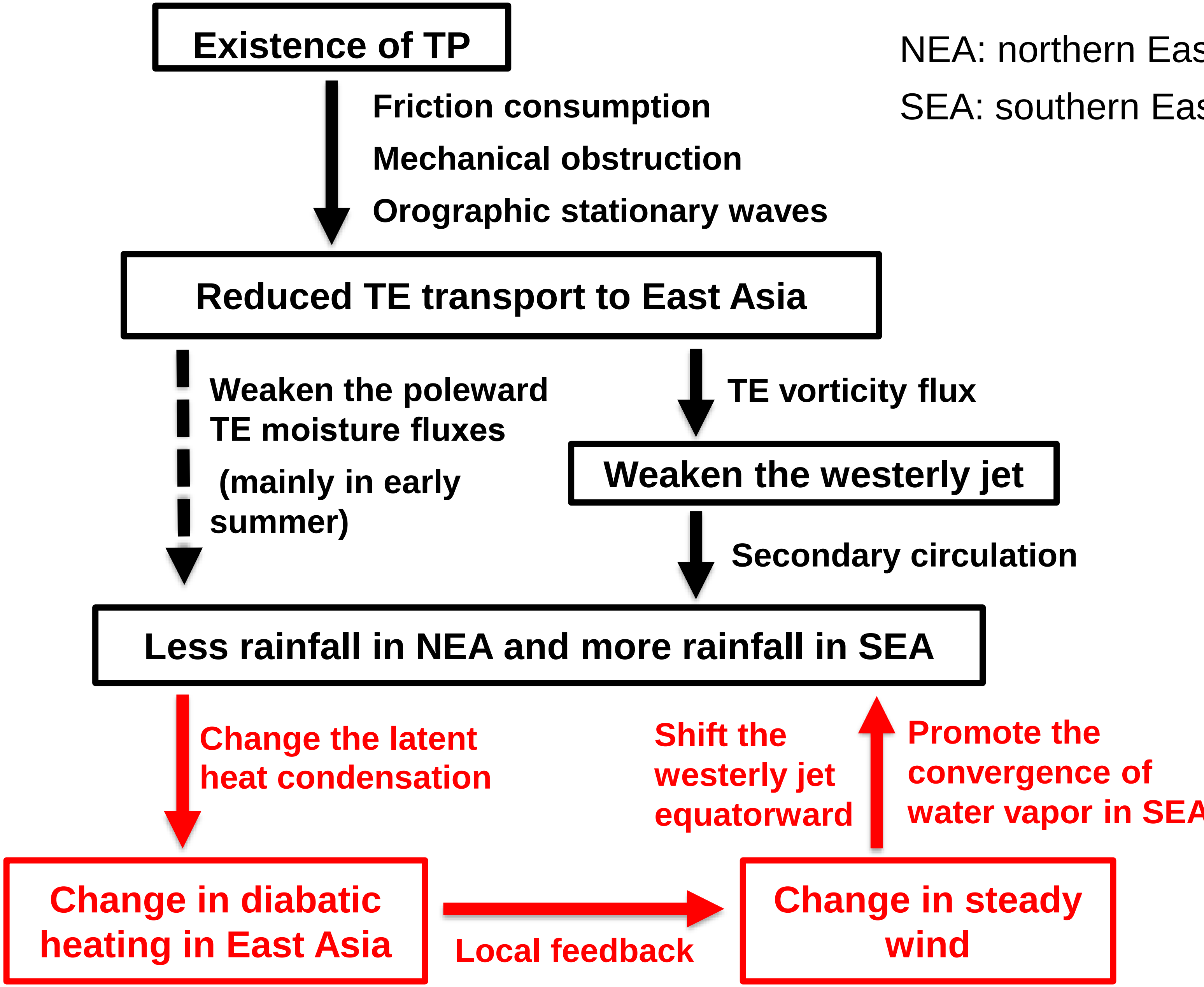
- **In late summer, sharp meridional moisture gradient over East Asia weakens and migrates north as the monsoonal southerlies advance to the Northeast China Plain, so do the poleward TE moisture fluxes, which means that the effect of TE moisture fluxes on East Asia weakens.**
- **Therefore, the change in TE moisture fluxes induced by the suppressed TE become too trivial to affect the distribution of water vapor.**
- **Without the cooperation of water vapor, anomalous divergent field at upper level alone can only resulted to the weak precipitation anomalies, indicating the important role of TE moisture transport in atmospheric circulation.**

Vertically-integrated transient moisture transport and its divergence (shading; positive values denote convergence)

5. Conclusion and Discussion

NEA: northern East Asia

SEA: southern East Asia



5. Conclusion and Discussion

- **While previous studies mainly focused on the thermal and mechanical roles of TP in EASM and assert that the existence of TP favors a poleward shift of East Asian summer rain belt through steady thermodynamic and dynamic forcing, this study qualitatively finds that the TP's inhibition of TE can shift the East Asian rain belt southward, shedding new insights in the theory about the climatic effects of TP.**

- **Since the rainfall anomalies caused by suppressed TE are similar to the decadal rainfall change pattern over East Asia which is always attributed to the external forcing such as the global warming and snow cover, the mechanism proposed in this work suggest that the atmospheric internal processes also can influence the variations of EASM. This possibility requires further investigation.**