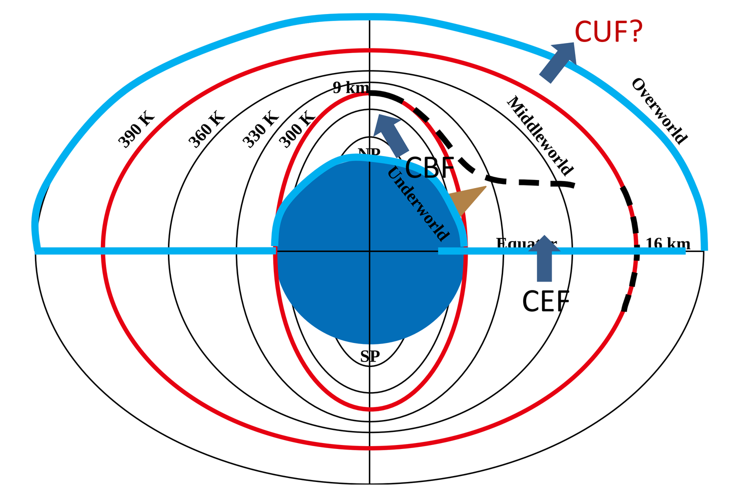
Aspects of potential vorticity circulation in the Northern Hemisphere: climatology and variation

Chen SHENG[1], Guoxiong WU[1,2*], Bian HE[1,2], Yimin LIU[1,2]
1. LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China
Corresponding author: Guoxion WU, gxwu@lasg.iap.ac.cn

This Paper

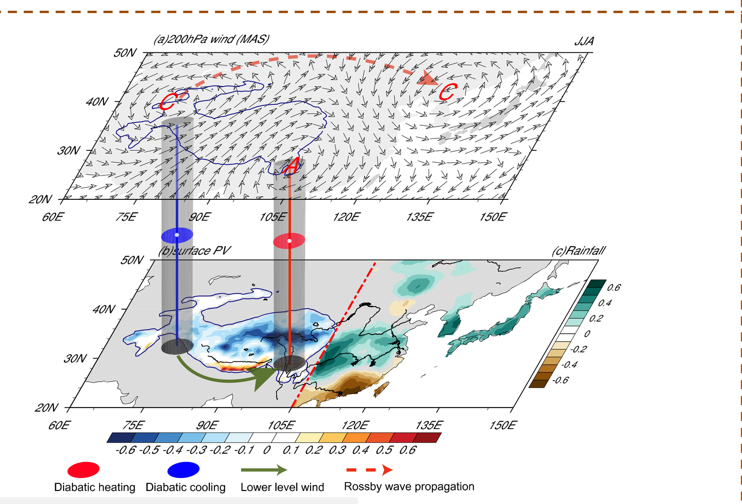
1.Introduction



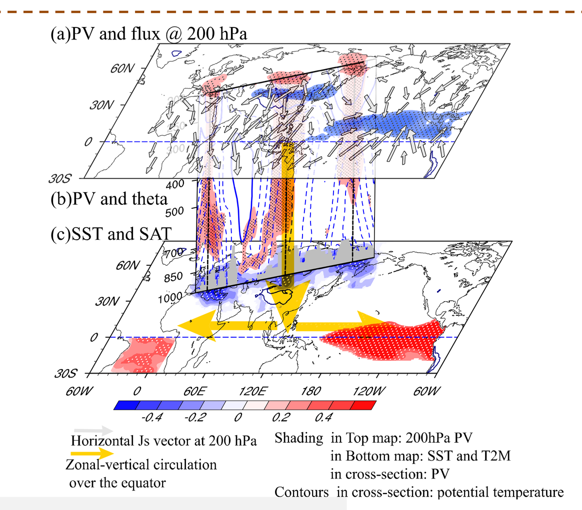
(Sheng et al., 2021; Hoskins, 1991)

Impermeability Theorem (Haynes and McIntyre, 1987;1990) VS Bretherton and Schär (1993), Egger et al. (2015). This study aims to answer

- whether the PVC (PV circulation) can cross the isentropic.
- If PVC can, how the cross-equatorial PVC (CEF) interacts with the cross-upper boundary PVC (CUF).



Surface boundary (Sheng et al., 2022a)



Lateral boundary (Sheng et al., 2022b)

2.Data and Diagnostic

- **Data: MERRA2 @ 1980-2020**
- **Diagnostic**

What is the PVC (PV circulation)?

PV density in flux form is

$$W = \nabla \cdot (\vec{\zeta_a}\theta)$$

By means of $\vec{J_C}$ expressed as

$$\vec{J_C} = -\vec{\zeta_a}\theta$$

We have

$$W = -\nabla \cdot (\vec{J_C})$$

$$\vec{J_C} = (J_C^x,\ J_C^y,\ J_C^p) = -\frac{\partial v}{\partial p}\theta\,\vec{i} + \frac{\partial u}{\partial p}\theta\,\vec{j} + (f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y})\theta\,\vec{k}$$

PVC is a vector whose convergence leads to positive PV.

How can the PVC work?

$$\begin{cases} \vec{A} = \vec{A_0} = \partial \vec{J_C} / \partial t \\ \vec{V_e} = \vec{V_e(A_0)} = \vec{A_0} / W \end{cases}$$

$$\frac{d\theta}{dt} = \frac{\partial \theta}{\partial t} + \vec{V_e(A_0)} \cdot \nabla\theta = \frac{\partial \theta}{\partial t} + \frac{\partial \vec{J_C}/\partial t}{W} \cdot \nabla\theta = -\theta \frac{\partial \ln|\vec{\zeta_a}|}{\partial t} \neq 0$$

PVC can cross the isentropic surface.

$$\iiint_{NH} W dv = \iiint_{NH} -\nabla \cdot (\vec{J_C}) dxdydp$$

$$Gross = \iint_{upper} -J_C^p \vec{k} \cdot (-\vec{k}) dxdy + \oint_{eq} \int_{p_T}^{ps} -J_C^y \vec{j} \cdot (-\vec{j}) dxdp + \iint_{bot} -J_C^p \vec{k} \cdot (\vec{k}) dxdy$$

$$= \underbrace{\iint_{upper} J_C^p dxdy}_{CUF} + \underbrace{\oint_{eq} \int_{p_T}^{ps} J_C^y dxdp}_{CEF} + \underbrace{\iint_{bot} -J_C^p dxdy}_{CBF}$$

The NH's gross PV depends solely on the total flux of PVC crossing the upper boundary, bottom, and cross-section along the equator.

3. Climate and variation

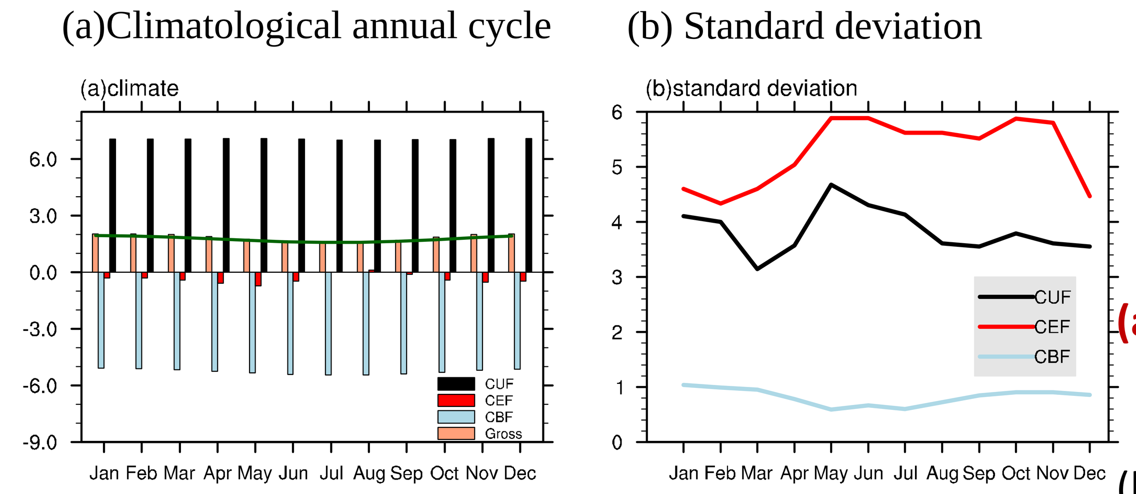


Fig1. Climatological annual cycle (a) and (b) standard deviation of CUF, CBF, CEF, and gross PV in the Northern Hemisphere (NH)

$$CUF = \iint_{upper} J_C^p dxdy = \theta_T \oint_{eq} u_T dx + \theta_T \iint_{upper} f\ dxdy$$

$$CEF = \oint_{eq} \int_{p_T}^{p_S} J_C^y dxdp = -\theta_T \oint_{eq} u_T dx + \theta_T \oint_{eq} u_\xi dx$$

$$CBF = \iint_{bot} -J_C^p dxdy = \iint_{bot} -(f + \zeta)\theta\ dxdy$$

(a) **Climate**: CUF is important in forming the positive basic sate of gross PV in the NH
(b) The climate CEF is smaller than that of the CUF, but their standard deviations (Fig. 1b) are comparable.

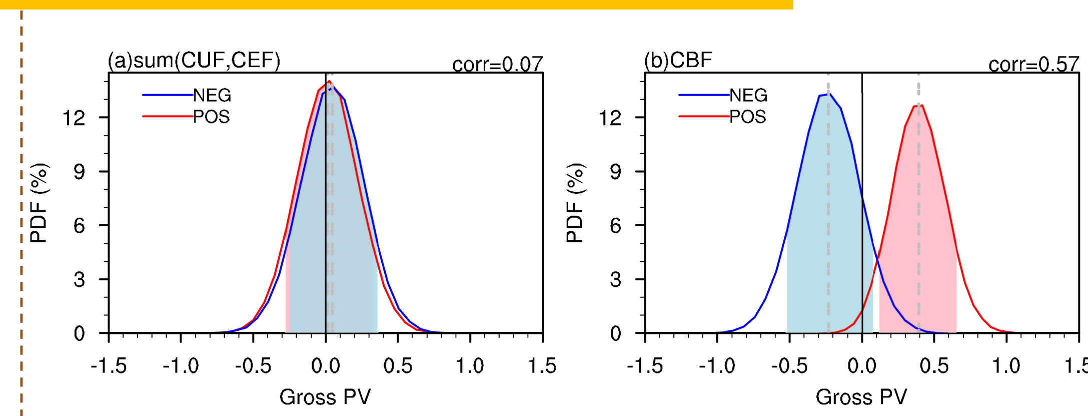


Fig2. PDF (colored line) and mean (vertical line) of the annual mean gross PV anomaly in NH. 100,000 bootstrapped sample.
(a) sum (CUF, CEF) in different phase of NH gross PV.
(b) CBF in different phases of NH gross PV

Monte Carlo bootstrapping shows that in the sense of variation

(a) Although the anomalous CUF and CEF are prominent (Fig 1b), their total effect contributes little to the gross PV anomaly. (**Cancel**)
(b) The gross PV anomaly is significantly determined by the CBF anomaly. (Sheng et al. 2022b)

4. Intrinsically cancellation between CUF and CEF

Why does the total effects of CUF and CEF hardly contribute to the variation of Gross PV in the NH?

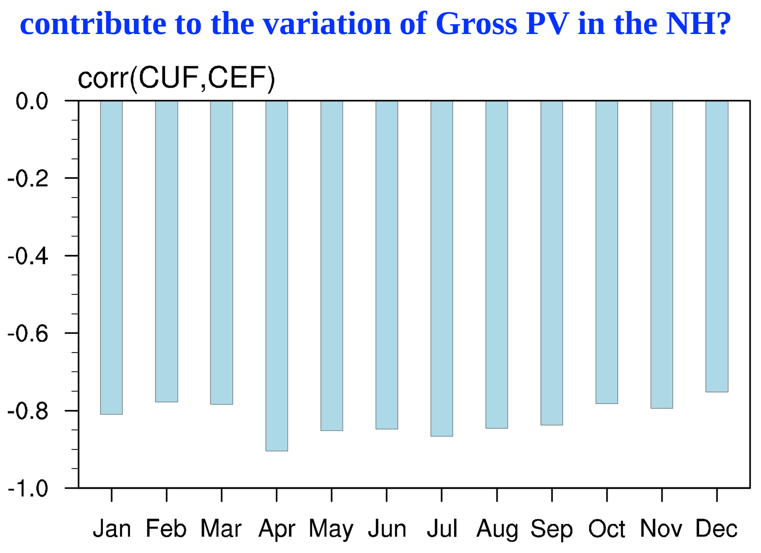


Fig3. Annual cycle of correlation coefficients between CUF and CEF.

A cancellation intrinsically rooted in the PV dynamics

$$CEF = \oint_{eq} \int_{p_T}^{p_S} J_C^y dxdp = \oint_{eq} \theta_T \int_{p_T}^{\xi} \frac{\partial u}{\partial p} dpdx = -\theta_T \oint_{eq} u_T dx + \theta_T \oint_{eq} u_\xi dx$$

Second mean value theorem for intrgrals
积分第二中值定理

$$CUF = \iint_{upper} J_C^p dxdy = \iint_{upper} (f + \zeta)\theta\ dxdy = \theta_T \oint_{eq} u_T dx + \theta_T \iint_{upper} f\ dxdy$$

Stokes curl theorem

Time anomaly

$$CEF' = (\oint_{eq} \theta_T \int_{p_T}^{\xi} \frac{\partial u}{\partial p} dpdx)' = (-\theta_T \oint_{eq} u_T dx)' + (\theta_T \oint_{eq} u_\xi dx)'$$

$$CUF' = (\iint_{upper} (f + \zeta)\theta_T dxdy)' = (\theta_T \oint_{eq} u_T dx)'$$

=> Zonal wind is the switch of anomalous PVC.

5. An implied PVC flow in the atmosphere

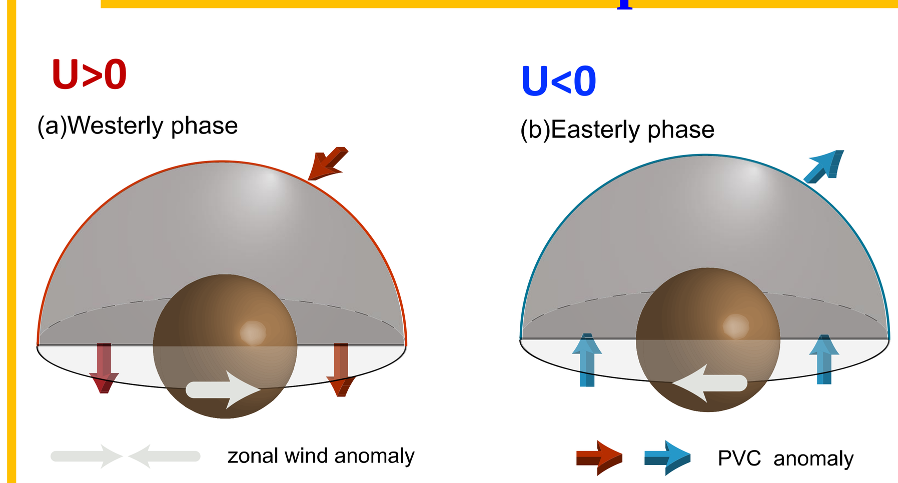
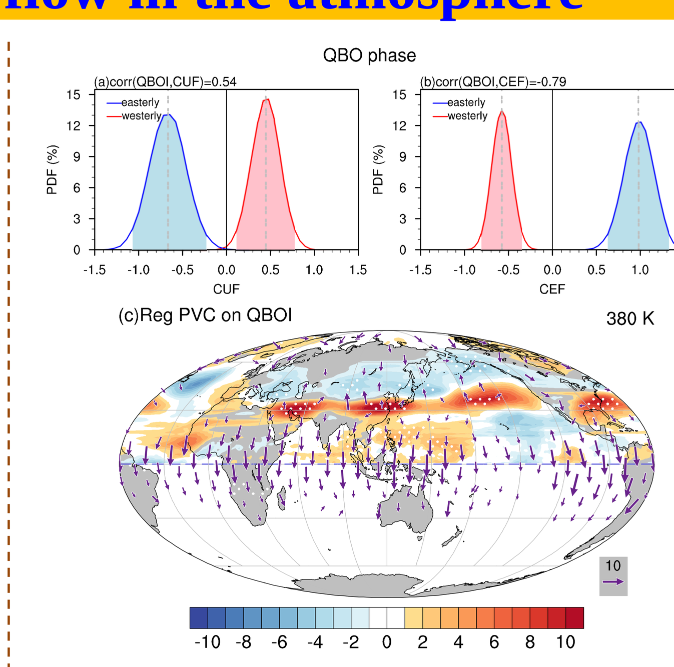


Fig4. Schematic diagram of PVC flow in the atmosphere.
(a) U>0. PVC inflows from the top and outflows from the equator.
(b) U<0. PVC outflows from the top and inflows from the equator.



Shading: 380-K PVC
Vector: vertical integral PVC

Fig5. Regressed 380-KPVC on QBO index (DJF).
(a) Westerly QBO phase: PVC inflows from top and outflows from equator.
(b) Easterly QBO phase: PVC inflows from top and outflows from equator.

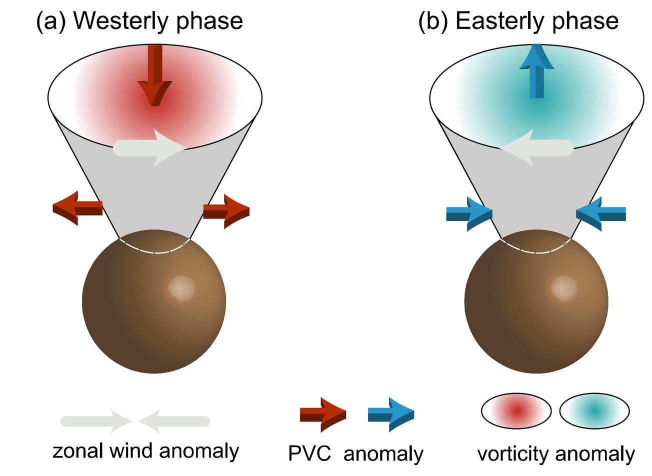
Conclusion

(1) Different from the HM flux, the PVC is theoretically proven to be able to cross the isentropic surface.

(2) In terms of climate, the climatological gross PV in the NH is largely controlled by the total effect of the CUF and CBF. In terms of variation, the variation of gross PV in the NH is largely determined by the CBF.

(3) The intrinsically cancellation, between CUF and CEF, sheds light on a seminal atmospheric process (Fig. 4) in which the zonal wind anomaly plays a decisive role. Westerly anomaly leads to an inflowing PVC from atmospheric top and outflowing PVC from the equator. The easterly anomaly corresponds to the opposite situation.

6. Future application and discussion



PVC pump (PV环流泵）

for gif version

Discussion
- Interaction between NH and SH

Application
- Interaction between upper- and lower-level
- Interaction between polar signal and mid-high latitudes signal.

Reference:
Sheng C, **Wu GX***, Tang YQ, et al. Characteristics of the potential vorticity and its budget in the surface layer over the Tibetan Plateau. International Journal of Climatology. 2021
Sheng C, **He B***, Wu GX, et al. Interannual influences of the surface potential vorticity forcing over the Tibetan Plateau on East Asian summer rainfall. Advances in Atmospheric Sciences: 2022a
Sheng C, **Wu GX***, He B, et al. Linkage between cross-equatorial potential vorticity flux and surface air temperature over the mid–high latitudes of Eurasia during boreal spring. Climate Dynamics: 2022b

Cite:
Sheng C, Wu GX*, He B, Yimin Liu. Aspects of potential vorticity circulation in the Northern Hemisphere: climatology and variation. Climate Dynamics: 2023

Chen SHENG: shengchen@lasg.iap.ac.cn