

Seasonal Characteristics of Atmospheric Circulation Response to Thermal Anomalies over the Tibetan Plateau: From Winter to Late Spring

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1. Introduction

Thermal forcing over the Tibetan Plateau (TP) affects atmospheric circulation, but its response varies with season. In the experiments examined here, TP warming produces a deep negative geopotential height response in December and a baroclinic response in May. Using LS4P experiments and a quasi-geostrophic geopotential tendency diagnosis, we identify the advection contributions underlying this contrast and examine their relationship with the seasonal background westerlies.

2. Methodology

- Model: UCLA GFS/SSiB2, based on NCEP-CFSv2 coupled with SSiB2.
- Cases: December 2016 and May 2024.
- Atmospheric response: EXP_LST/SUBT – EXP_CTRL.
- Observations: GHCN_CAMS monthly mean surface air temperature.

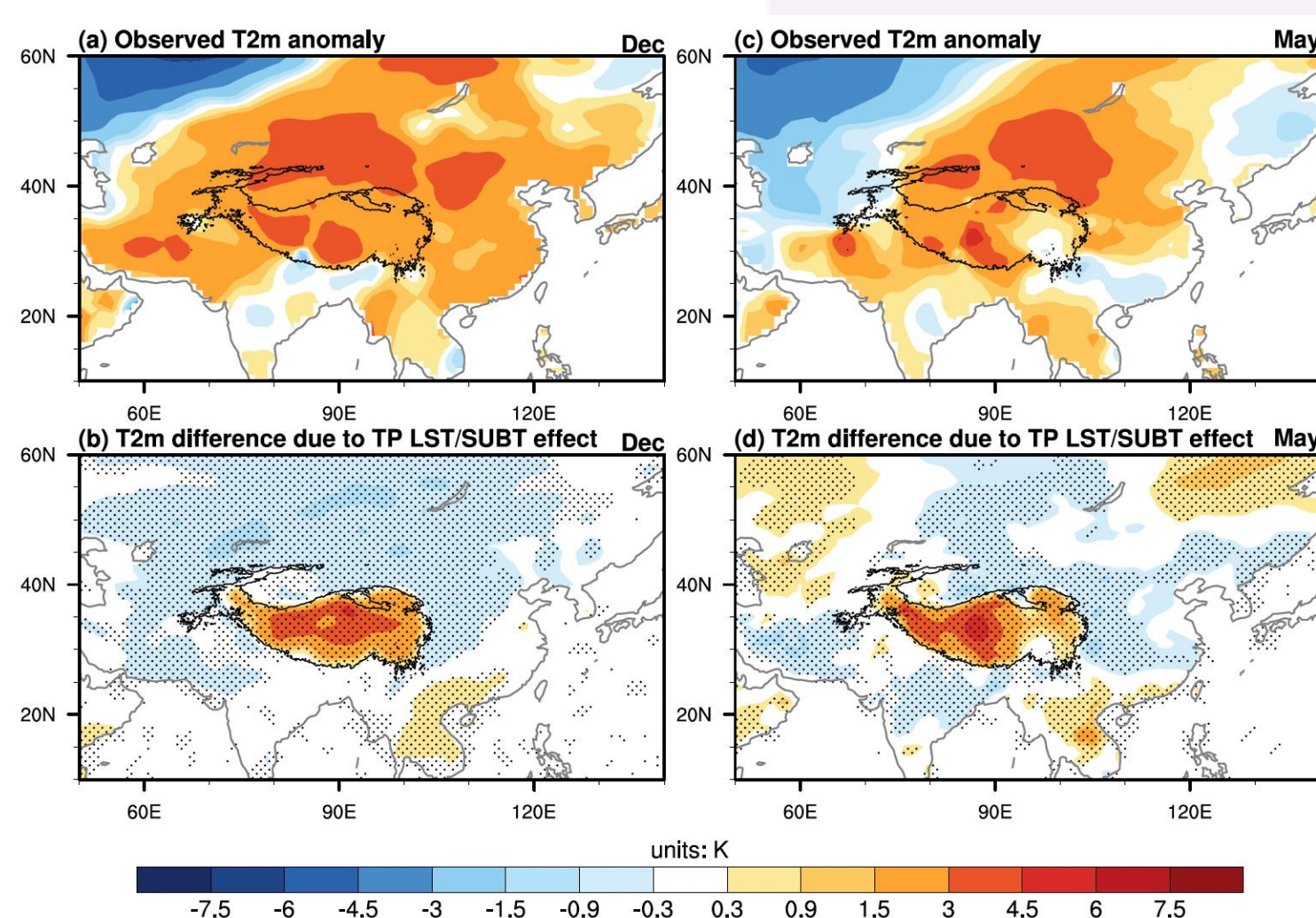


Figure 1 Surface air temperature (T-2m) anomalies from observations and model simulations. (a) Observed anomalies for December 2016. (b) Simulated anomalies for December 2016 with TP masking. (c-d) Same as (a) and (b), respectively, but for May 2024. The dotted grids denote the statistical significance based on the Student T-test at the $p < 0.1$ level.

Simulated TP warming resembles the observed pattern.

The quasi-geostrophic geopotential height tendency equation

$$\underbrace{\left(\frac{1}{f_0} \nabla^2 + \frac{f_0}{\sigma_1 p} \frac{\partial^2}{\partial p^2} \right)}_{\text{linear operator}} \underbrace{\left(\frac{\partial \Phi}{\partial t} \right)}_{\text{relative vorticity advection}} = \underbrace{-\vec{V}_h \cdot \nabla_h \zeta}_{\text{planetary vorticity advection}} + \underbrace{-\vec{\beta} \vec{v}}_{\text{residual (diabatic heating)}} - \underbrace{\vec{V}_h \cdot \nabla_h \left[-f_0 R \frac{\partial}{\partial p} \left(\frac{T}{\sigma_1 p} \right) \right]}_{\text{temperature advection}} + \underbrace{\vec{R}e}_{\text{residual}} \quad \text{A4}$$

A1 A2 A3

3. Results

3.1 Seasonal contrast in the geopotential height response

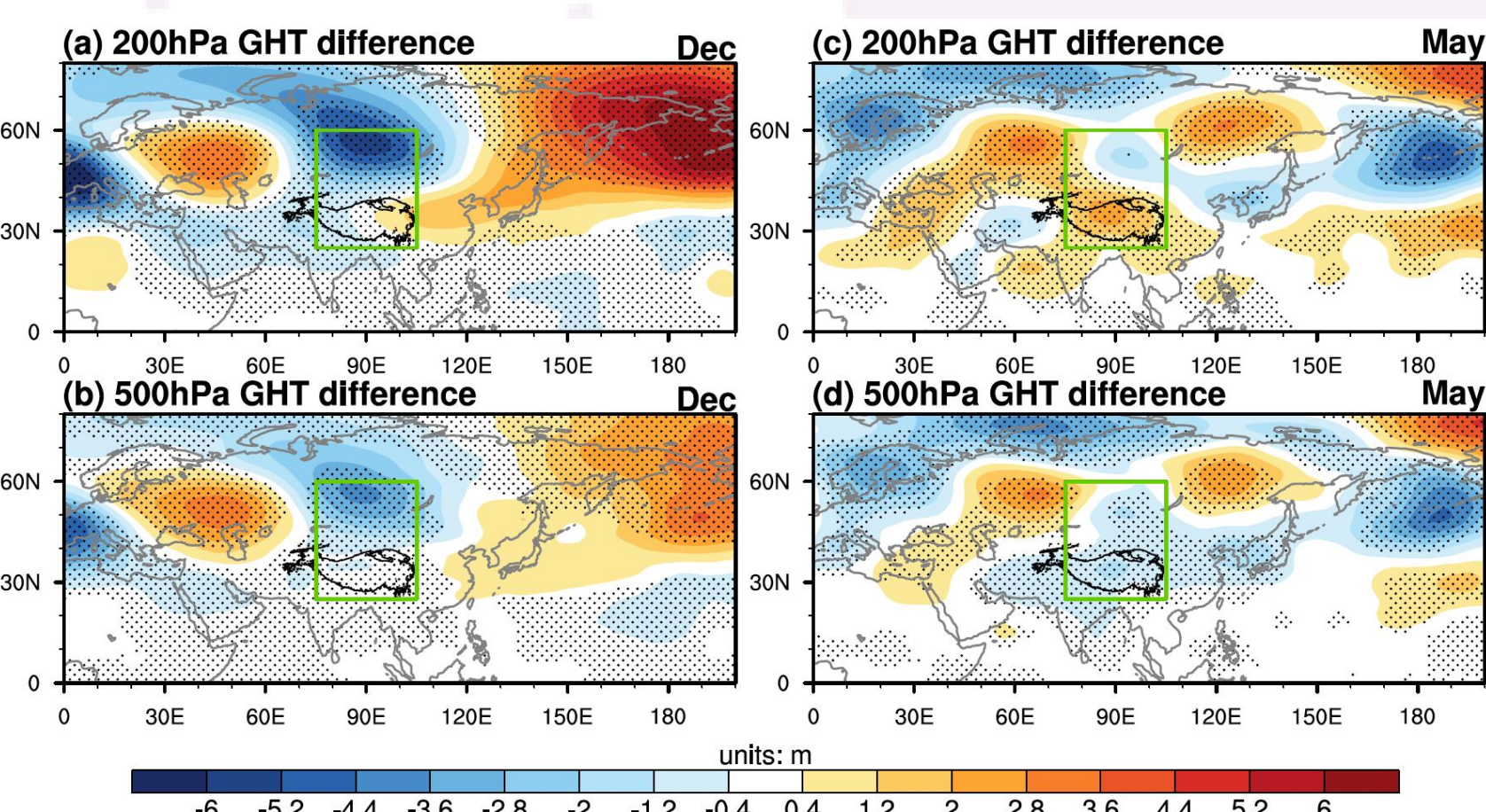


Figure 2 Geopotential height anomalies induced by the TP LST/SUBT effect. (a, c) Results at 200 hPa for (a) December 2016 and (c) May 2024. (b, d) Same as (a, c), but for 500 hPa. Green boxes outline the main region of the study (25–60N, 75–105E). The dotted grids denote the statistical significance based on the Student T-test at the $p < 0.1$ level.

In **Winter**, a **quasi-barotropic** negative anomaly occurs north of and over the TP. In **Late Spring**, the response evolves into a **baroclinic** structure over the TP, and the northern anomaly weakens.

Budget analysis shows that:

- A3** contributes negative height tendencies at lower levels in both seasons.
- A1** changes from negative in winter to positive in late spring, accounting for the upper-level seasonal contrast.

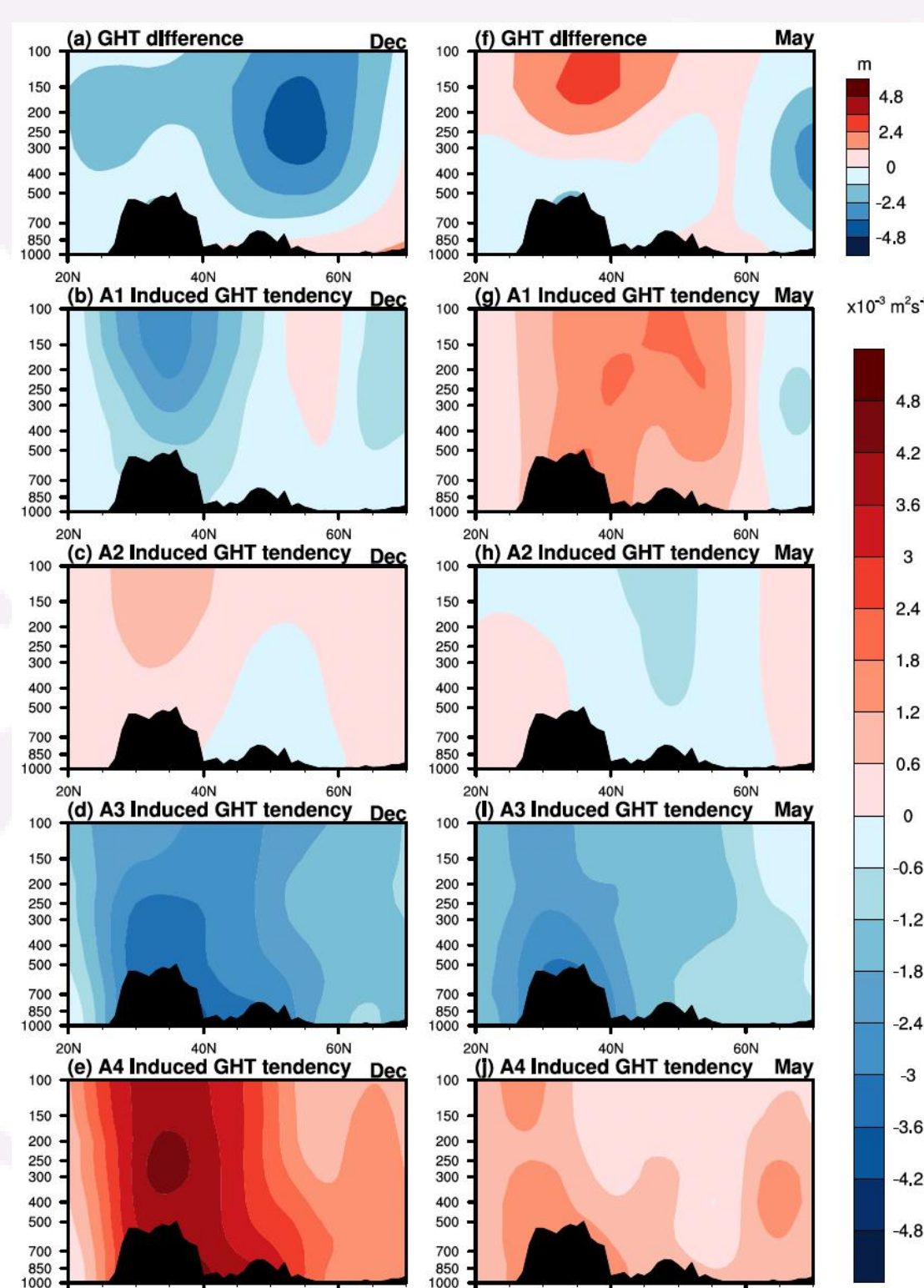


Figure 3 Latitude-height sections of the differences in geopotential height and dynamic forcing terms due to the TP LST/SUBT effect averaged over 75–105° E. (a) Geopotential height (m^2s^{-2}) and (b–e) contributions to the geopotential height tendency (m^2s^{-3}) induced by terms A1–A4 for December 2016. (f–j) Same as (a–e), but for May 2024. The black shading in all panels represents the terrain of the TP in this and the following figures.

The seasonal background westerlies modulate the circulation response to TP warming (Fig. 9):

- Winter (Quasi-barotropic):** Negative A1 contributions aloft and A3 contributions below favor a quasi-barotropic negative height response.
- Late Spring (Baroclinic):** Positive A1 contributions aloft and negative A3 contributions below favor a baroclinic response.

Accurate representation of the background jet is therefore important for assessing TP-related S2S predictability.

3.2 The Persistent Contribution from Temperature Advection

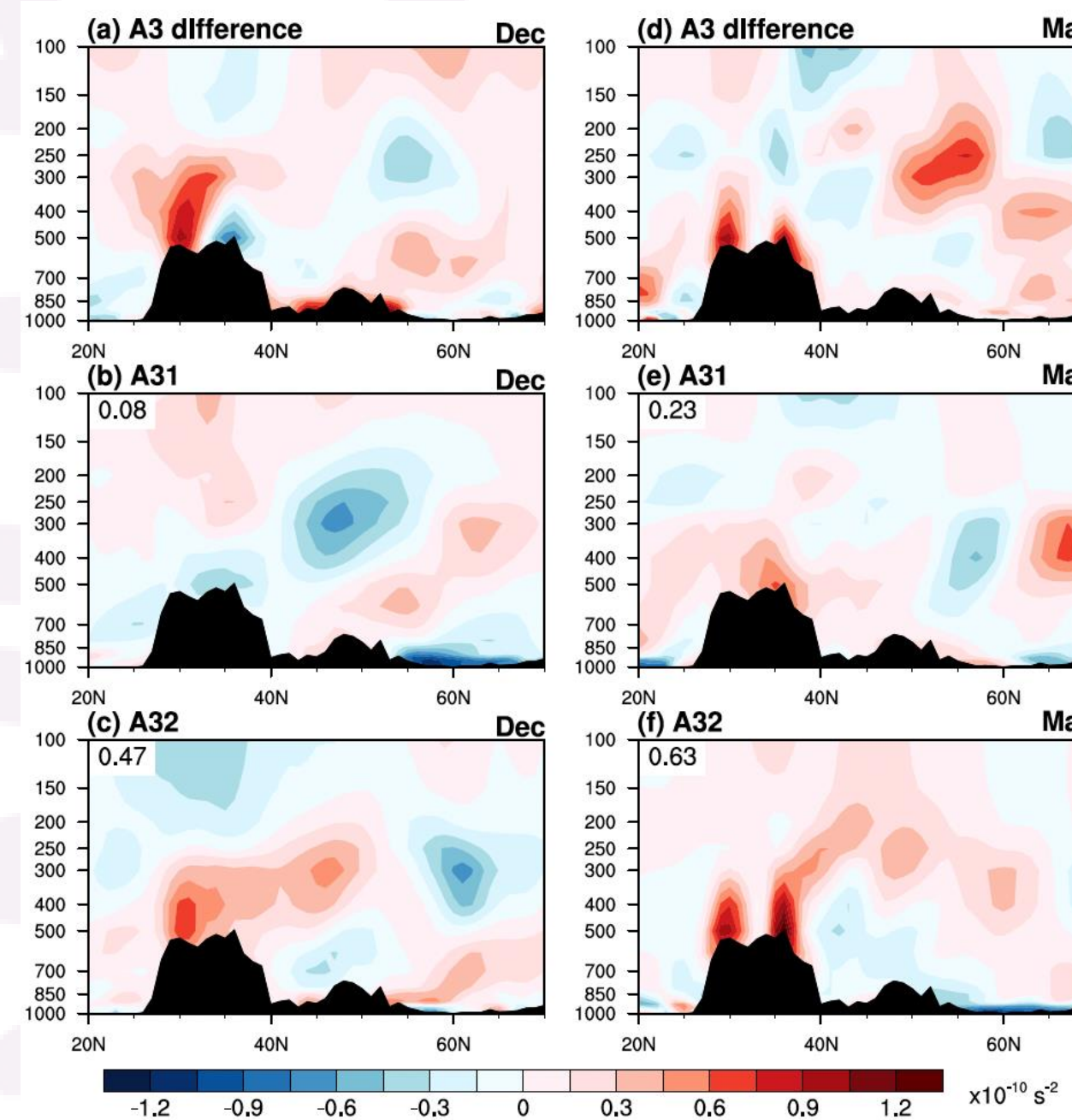


Figure 4 Latitude-height sections of the differences in temperature advection (A3) and its components due to the TP LST/SUBT effect averaged over 75–105° E. (a) Total A3 (s^{-2}). (b) Zonal component (A31); and (c) Meridional component (A32) for December 2016. (d–f) Same as (a–c), but for May 2024. The number in the top-left corner indicates the pattern projection coefficient of that specific component to the total anomaly over the domain 25–60° N.

$$\Delta A3 = \underbrace{\frac{f_0 R}{\sigma_1 p} \cdot \frac{\partial}{\partial p} \Delta \left(u * \frac{\partial T}{\partial x} \right)}_{A31} + \underbrace{\frac{f_0 R}{\sigma_1 p} \cdot \frac{\partial}{\partial p} \Delta \left(v * \frac{\partial T}{\partial y} \right)}_{A32}$$

The **meridional component A32** makes the larger contribution to the leading-order A3 forcing in both cases. Its contribution depends on the vertical variation of the meridional temperature-advection.

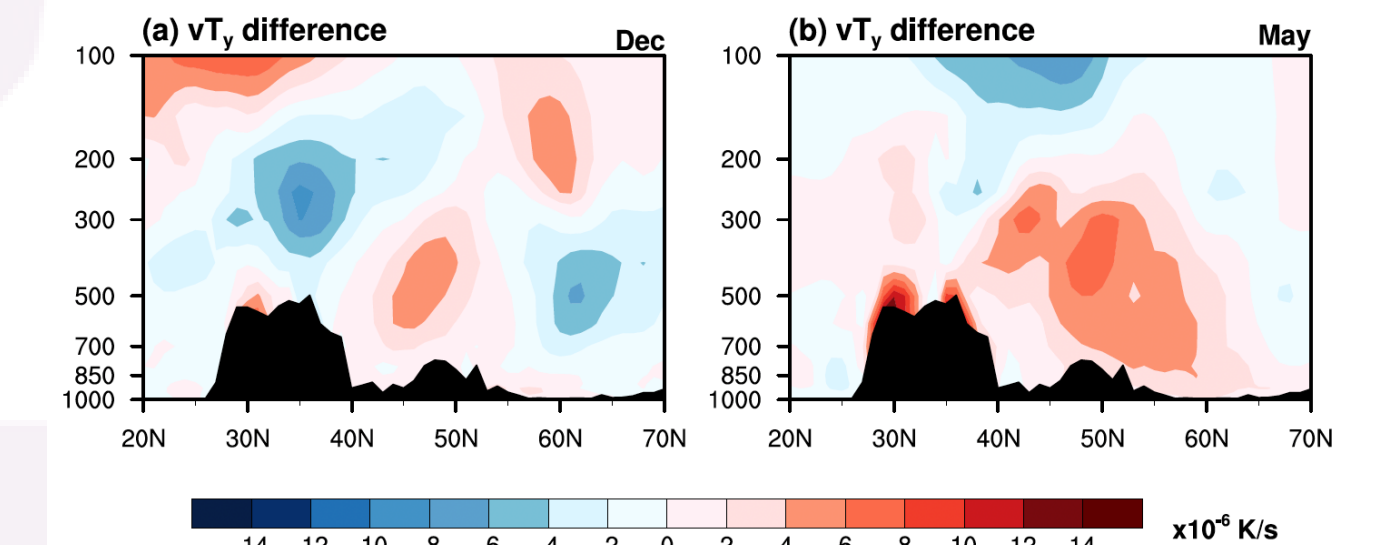


Figure 5 Latitude-height sections of the difference in meridional temperature advection due to the TP LST/SUBT effect averaged over 75° E–105° E. (a) $\Delta(vT_y)$ for December 2016 and (b) same as (a), but for May 2024.

3.3 The Seasonal Relative Vorticity Advection

$$\Delta A1 = \Delta \left(-u \frac{\partial \zeta}{\partial x} - v \frac{\partial \zeta}{\partial y} \right) = \underbrace{-\Delta u * \frac{\partial \zeta}{\partial x}}_{A11} - \underbrace{\bar{u} * \Delta \frac{\partial \zeta}{\partial x}}_{A12} - \underbrace{-\Delta v * \frac{\partial \zeta}{\partial y}}_{A13} - \underbrace{-\bar{v} * \Delta \frac{\partial \zeta}{\partial y}}_{A14} + R_v$$

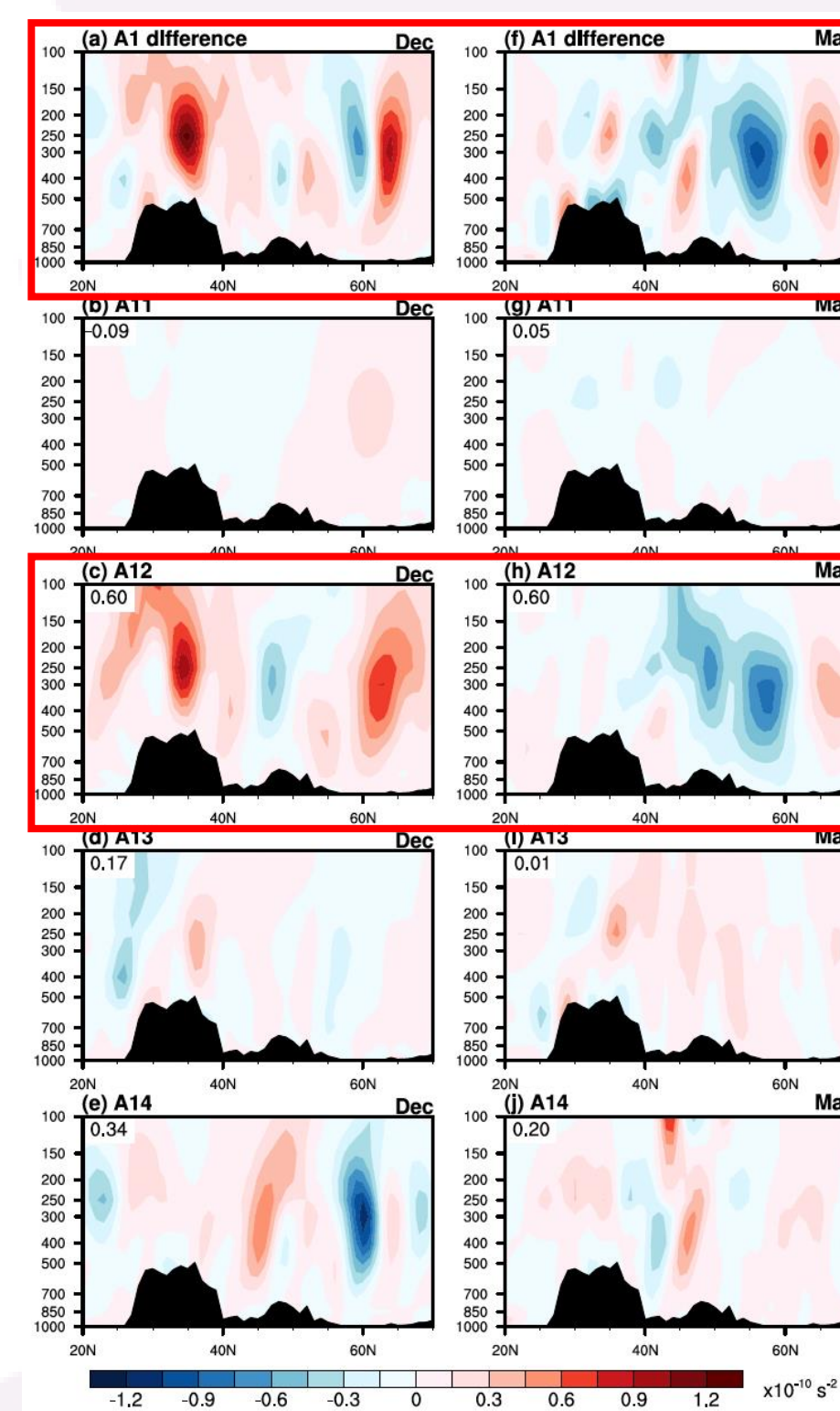


Figure 6 Latitude-height sections of differences in relative vorticity advection (A1) and its linear components due to the TP LST/SUBT effect averaged over 75–105° E.

Winter: Strong westerlies displace the anomaly eastward, favoring A1-induced height falls over the TP.

Late Spring: Weaker westerlies retain the anomaly near the TP, favoring A1-induced height rises aloft.

The response is driven by the anomalous **zonal vorticity gradient (A12)**

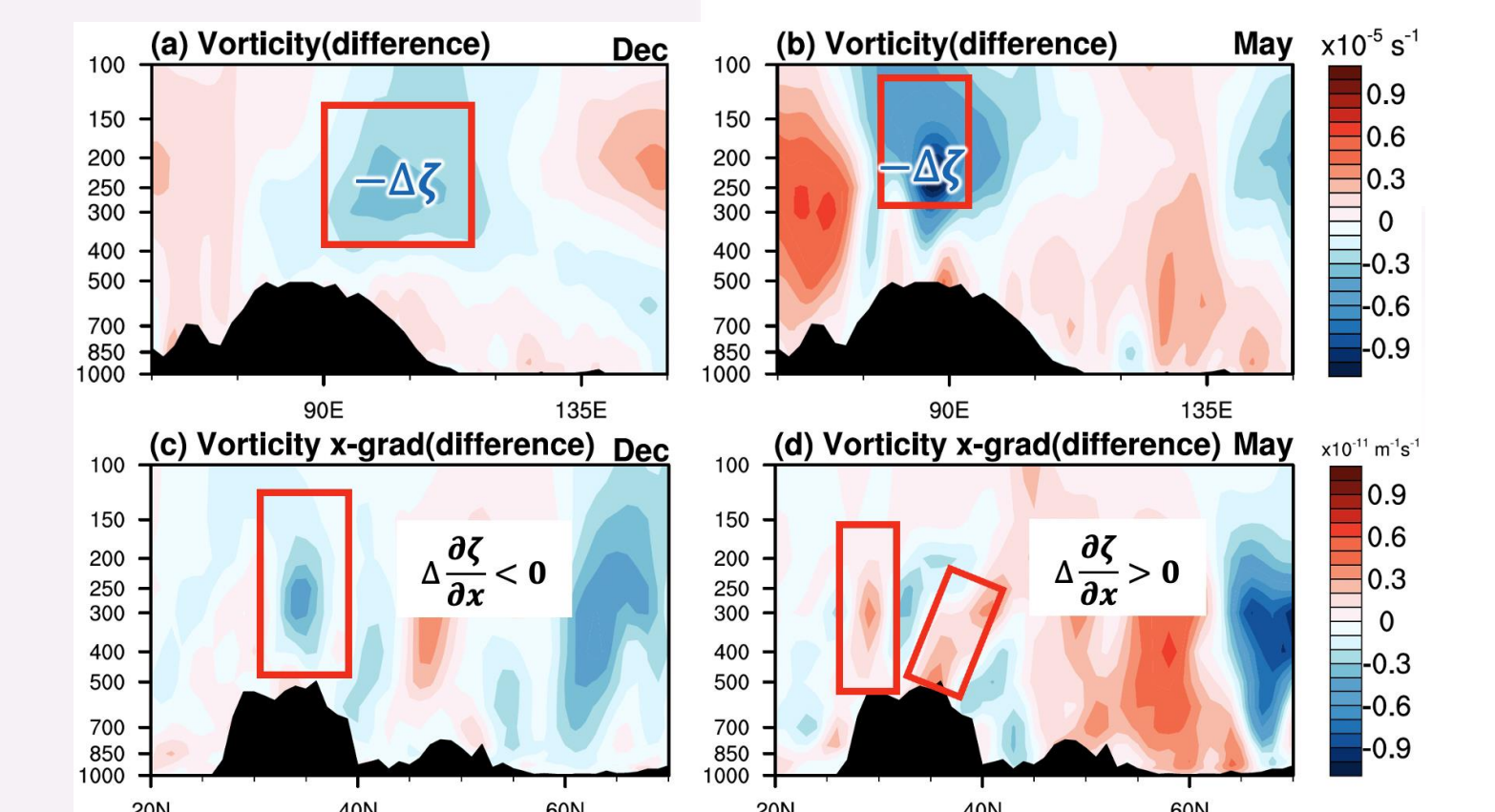


Figure 7 Latitude-height sections of the zonal gradient of vorticity difference (m^3s^{-1}) averaged over 75–105° E for (a) December 2016 and (b) May 2024. Longitude-height sections of the vorticity difference (s^{-1}) averaged over 29–38° N for (c) December 2016 and (d) May 2024.

TP surface warming induces an upper-level anticyclone (negative vorticity).

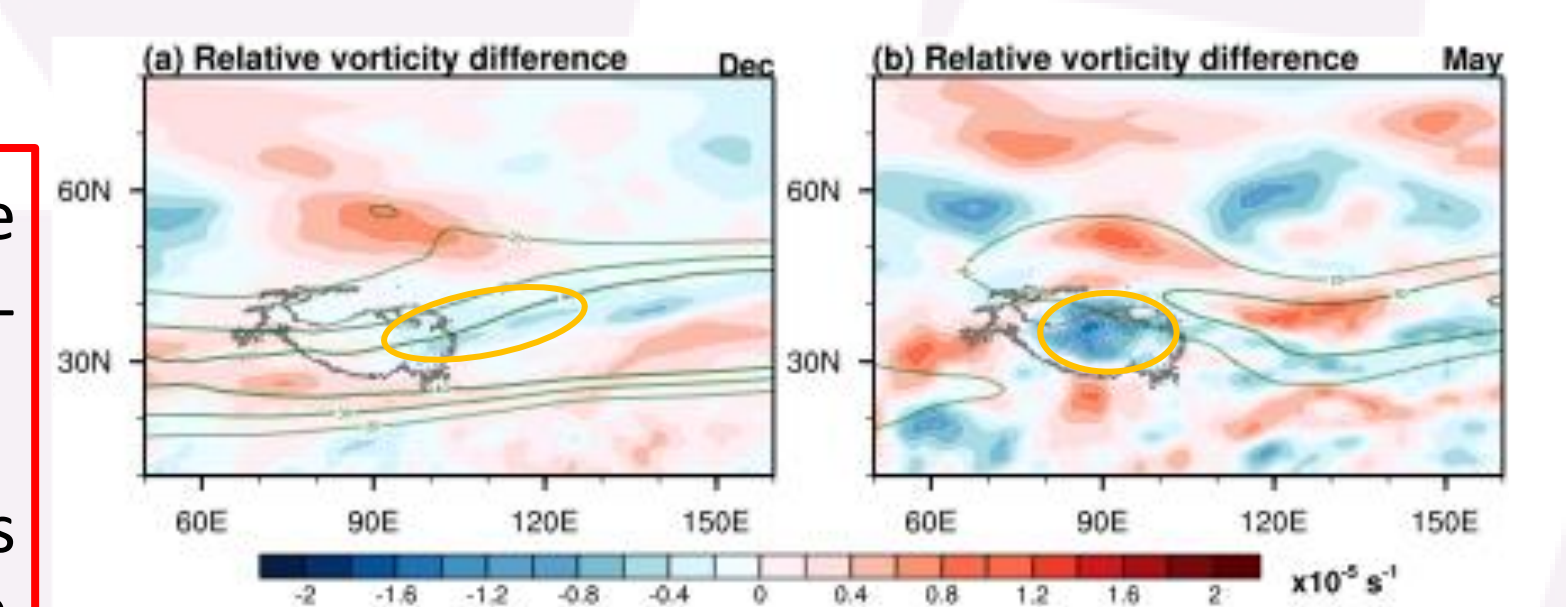


Figure 8 Relative vorticity difference at 200 hPa due to the TP LST/SUBT effect. (a) December 2016 and (b) May 2024. Shading denotes the relative vorticity difference (s^{-1}). Green contours denote the background zonal wind at 20, 30, and 40 m/s.

4. Conclusion

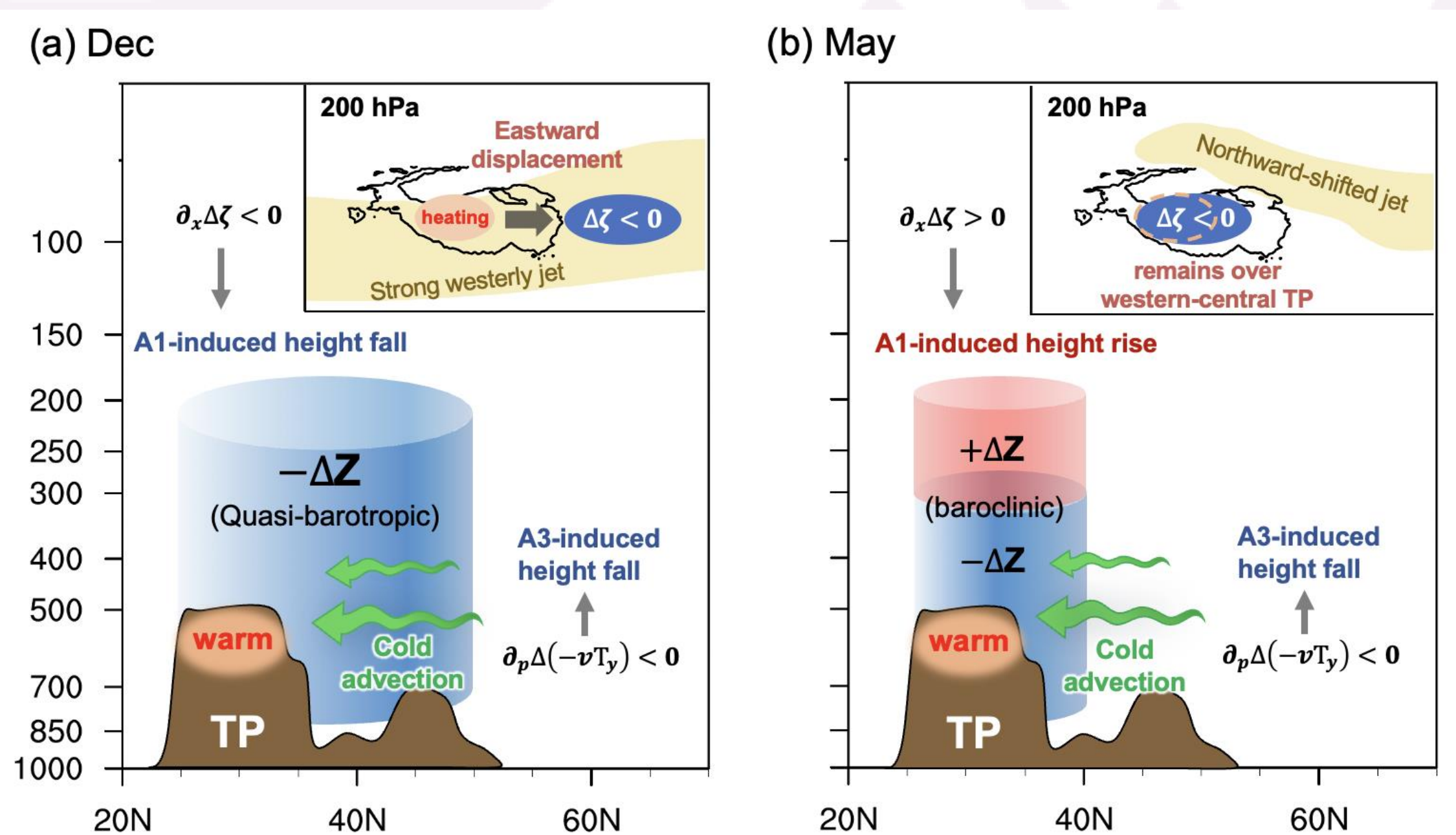


Figure 9 Schematic of the mechanisms underlying the seasonally contrasting geopotential height responses to Tibetan Plateau surface heating.