To what extent can the Ozone Valley over the Tibetan Plateau influence the East Asian summer precipitation?

Lingaona Zhu
Fudan University

Zhiwei Wu (zhiweiwu@fudan.edu.cn)
Fudan University https://orcid.org/0000-0002-8163-2215

Article

Keywords:

Posted Date: June 21st, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3067899/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: (Not answered)

Version of Record: A version of this preprint was published at npj Climate and Atmospheric Science on November 1st, 2023. See the published version at https://doi.org/10.1038/s41612-023-00508-x.
To what extent can the Ozone Valley over the Tibetan Plateau influence the East Asian summer precipitation?

Lingaona Zhu, Zhiwei Wu

Department of Atmospheric and Oceanic Sciences, Institute of Atmospheric Sciences, and Shanghai Scientific Frontier Base of Ocean-Atmosphere Interaction, Fudan University, Shanghai 200438, China

Submitted to npj Climate and Atmospheric Science

June 15, 2023

*Corresponding author:

Prof. Zhiwei Wu

Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences, Fudan University, 2005 Songhu Rd, Yangpu, Shanghai 200438, China

Email: zhiweiwu@fudan.edu.cn
ABSTRACT

The ozone valley over the Tibetan Plateau (OVTP) has experienced significant interannual variations during the past decades. Previous studies have primarily focused on the origins of OVTP, while the climate impact of OVTP is still an open question. This study reveals that OVTP during its peak season (May-July) explains approximately 15% of the summer precipitation variability in East Asia. The results suggest that the surface temperature ($T_s$) anomaly over the Tibetan Plateau (TP) acts as a link between OVTP and East Asian precipitation. Causality analysis confirms that the intensification of OVTP leads to a significant increase in $T_s$ over northwestern TP. Through a positive land-atmosphere feedback, the $T_s$ anomaly over the TP is amplified. The anomalous $T_s$ pattern persists into summer (June-August) due to the land memory effect and impacts the East Asian precipitation by modulating the local circulation. Numerical experiments show that diabatic heating over the TP induces an anomalous anti-cyclone centered over the Yangtze-Huaihe River Basin, leading to negative precipitation anomalies in the Yangtze River Basin and positive precipitation anomalies in southern China. Our analysis of Coupled Model Intercomparison Project Phase 6 models reveals that more accurate prediction of East Asian precipitation requires improved understanding of the relationship between OVTP and TP $T_s$. 
INTRODUCTION

Ozone layer not only provides local heating in the stratosphere but also absorbs ultraviolet radiation to protect the Earth. Therefore, ozone depletion could modulate the global radiative balancing and affect tropospheric climate. Since then, several ozone depletions have been discovered and studied, including the ozone holes over the Antarctic and the Arctic, as well as the ozone valley over the Tibetan Plateau (OVTP).

Previous studies have suggested that the depletion of polar stratospheric ozone has been responsible for most tropospheric circulation changes in the Southern Hemisphere during the austral summer over the second half of the twentieth century. Antarctic ozone depletion leads to cooling and intensification of the polar vortex, along with a poleward shift of the mid-latitude jet stream. This process enhances the positive phase of the Southern Hemisphere annular mode and expands the Hadley cell, consequently impacting surface temperature and subtropical precipitation in the Southern Hemisphere during the austral summer. Although the ozone depletion in the Arctic region has been less pronounced compared to the Antarctic region in the past 30 years, it is still associated with the strengthening of the polar vortex and a notable and persistent shift in the tropospheric circulation towards a positive phase of the Northern Annular Mode. Consequently, positive temperature anomalies are observed at the surface in Northern Europe and Siberia, while negative temperature anomalies are observed in China, Greenland, and northeastern Canada. Furthermore, polar ozone depletion also exerts a substantial influence on polar sea ice, with certain effects
attributed to cloud radiative processes\textsuperscript{12,15}. These results emphasize the essential impact of ozone depletion in polar regions.

Ozone depletion is not exclusive to polar regions, but also occurs in mid-latitude regions. As early as 1995, a notable total column ozone (TCO) depletion center was discovered over the TP in summer using the Total Ozone Mapping Spectrometer satellite data\textsuperscript{16}. Subsequent research confirmed the existence of the OVTP based on the analysis of ozone soundings data collected in Lhasa from June to October 1998\textsuperscript{17}. Furthermore, the OVTP was observed to exhibit a double core structure, with a stronger center in the upper troposphere-lower stratosphere (UTLS) region and a weaker center in the upper stratosphere\textsuperscript{18}. Since the discovery of OVTP, numerous studies have been dedicated to identifying the factors responsible for its formation\textsuperscript{19-32}. Some studies emphasized the role of chemical processes in driving the ozone depletion over the TP\textsuperscript{19-21}, while others claimed that the influence of the topography of the TP was more crucial than the chemical effect\textsuperscript{22-26}. Noticeably, the dominant causes of OVTP formation, according to most studies, are associated with dynamic effects. During summertime, the TP exerts a substantial thermal and dynamic influence on the surrounding atmospheric circulation\textsuperscript{16}. As a result, the air in the lower troposphere, which contains lower ozone content compared to the stratosphere, is efficiently transported upward, resulting in a reduction in ozone concentrations at higher altitudes over the region as well as in the TCO. Additionally, the process of stratosphere-troposphere mass exchange\textsuperscript{21, 27, 28}, variations in atmospheric circulation associated with the Asian
summer monsoon$^{29-31}$, and the uplift of isentropic surfaces and tropopause height$^{22, 32}$ are also recognized as vital contributors to the formation of the OVTP.

Being one of the prominent ozone depletion centers in the world, however, the climate impact of the OVTP has received limited attention in previous studies$^{29, 33-35}$. Interactions between the intensity of the South Asia High (SAH) and ozone in neighboring regions during summertime have been indicated in several studies$^{33, 34}$. Li et al. (2017) suggested that the latitudinal asymmetry of ozone in the UTLS region could induce a latitudinal asymmetry in radiative forcing within the South Asian high-pressure system, which in turn had the potential to affect the South Asian High.

Additionally, previous research has shown a close correlation between the variation of total ozone over the TP and the temperature and precipitation patterns in China$^{35}$, while the corresponding physical mechanisms still require further investigation and validation. Therefore, it is meaningful to investigate the extent to which the OVTP can influence East Asian summer precipitation and elucidate the corresponding physical mechanism.

Zhou and Zhang (2005) suggested, based on observation data, that the OVTP may contribute to the cooling in the stratosphere and warming in the troposphere over the TP in recent decades$^{29}$. Considering the substantial impact of the thermal anomalies over the TP on the East Asian climate$^{36-40}$, it is worthwhile to investigate whether the OVTP can influence East Asian precipitation by modifying the thermal anomalies of the TP. In this study, we discover the significant impact of the May-July (MJJ) OVTP on the East Asian summer monsoon and illustrate the corresponding physical mechanisms. The structure of the paper is organized as follows. Section 2 describes the
relationship between OVTP and East Asian summer precipitation. Impact of the MJJ
OVTP on the summer TP thermal anomaly is evaluated in section 3. Section 4 provides
a linear response of circulation anomaly over East Asia to the TP diabatic heating
anomaly.

RESULTS

Relationship between the OVTP and the East Asian summer precipitation

To characterize the OVTP, the monthly zonal ozone deviation obtained by
subtracting the zonal mean from the TCO is calculated over the Tibetan region (75°-
105°E, 25°-45°N)\(^\text{32, 41, 42}\). The result indicates that the strongest zonal ozone deviation
period over the TP occurs from May to July during 1979-2022 (not shown). Therefore,
we investigate the climate effects induced by the OVTP during these three months.

Based on the spatial distribution of the OVTP climatology over the past 44 May-July
(MJJ) periods (Fig. 1a), the strongest ozone valley is located over the north-western TP,
reaching around -36 DU. To quantitatively measure the interannual variations of the
MJJ OVTP, the OVTP index OVTP\(_I\) is defined as the inverse TCO zonal deviation
averaged within the red-boxed area (70°-95°E, 32.5°-42.5°N) in Fig. 1a. Specifically, a
higher OVTP\(_I\) value indicates a stronger OVTP. Consistent with the results in the earlier
studies\(^\text{32, 41, 42}\), the time series of the MJJ OVTP\(_I\) (Fig. 1b) exhibits an interannual
variability with no significant trend.

To illustrate the association between OVTP\(_I\) and East Asian summer precipitation,
the regression of East Asian summer precipitation anomalies against the MJJ OVTP\(_I\) is
plotted in Fig. 2. Corresponding to the strengthening of the MJJ OVTP, the precipitation
distribution shows a north–south dipole pattern, characterized by negative precipitation anomalies along the Yangtze River Basin to southern Japan while positive precipitation anomalies in the Indochina Peninsula and southern China region. The MJJ OVTPI explains about 6 to 20% of the total variance of the local JJA precipitation along the Yangtze River Basin to southern Japan, and accounts for approximately 6 to 12% of the total variance of the local JJA precipitation in the Indochina Peninsula and southern China region (Fig. 2b).

To further explain the observed precipitation pattern, the geopotential height and wind anomalies at different pressure levels (200 hPa, 500 hPa, and 850 hPa) regressed against the OVTPI are examined (Fig. 3). At 200 hPa, there is a distinct north-south dipole pattern in geopotential height anomalies. A positive anomaly center is located over north-eastern China, while a negative anomaly center is observed over southern China. Meanwhile, a positive anomaly center in geopotential height is observed over the northwestern Pacific at 500 hPa. At 850 hPa, high pressure anomalies are found over the northwestern Pacific, corresponding to negative precipitation anomalies along the Yangtze River Basin to southern Japan (Fig. 2a). Concurrently, easterly wind anomalies along the southeastern coast of China contribute to the transport of moisture, leading to the observed positive precipitation anomalies in southern China (Fig. 2a).

Therefore, the question arises: how does the preceding OVTPI influence summer circulation patterns and lead to the observed precipitation anomalies in East Asia?

Previous studies have provided evidence that ozone in the UTLS region significantly influences the radiation budget and surface temperature\textsuperscript{29, 43-45}. Additionally, the
thermal anomaly of the TP has been shown to impact East Asian precipitation\textsuperscript{36-40, 46}. Based on the studies above, we have formulated a hypothesis: can the OVTP influence East Asian precipitation by modifying the surface temperature of the TP? To explore this hypothesis, we first need to investigate the impact of the preceding OVTP on the summer TP thermal anomaly.

**Impact of the MJJ OVTP on the JJA TP thermal anomaly**

Vertical-latitude cross sections along 70°-95°E in MJJ are depicted in Fig. 4. Corresponding to the intensification of the OVTP, negative TCO anomalies are observed at altitudes ranging from 50 to 300 hPa, with a particularly significant depletion occurring around 150 hPa. Due to the depletion of ozone in the UTLS over the TP, less ultraviolet radiation is absorbed in lower stratosphere, resulting in an increased amount of radiation reaching the troposphere and the TP surface\textsuperscript{29}. As a result, a prominent feature is the occurrence of negative temperature anomalies above 150 hPa, while positive temperature anomalies occur below this height (Fig. 4b). Additionally, cooling in the stratosphere is favorable for air mass descent\textsuperscript{29}. The subsidence of cooled air masses above 100 hPa can result in a positive anomaly of high pressure around 150 hPa. The observed phenomenon and the physical mechanism described here are consistent with the findings of Zhou and Zhang (2005), which suggest that ozone depletion is likely an important external forcing in influencing temperature and general circulation in the TP region. Moreover, the high pressure anomaly around 150 hPa would lead to a reduction in low cloud cover\textsuperscript{47, 48}, which in turn amplifies the $T_s$ anomaly over TP.
To verify the causality of the physical mechanism described above, the Liang-Kleeman information flow method has been used. Based on the physical interpretations of the results obtained from the information flow method, the negative rates of information flow values indicate that MJJ OVTPI tends to stabilize or enhance the predictability of MJJ TP temperature (30-140 hPa and below 300 hPa) (Fig. 5a) and geopotential height (70 to 500 hPa) (Fig. 5b). Additionally, the information flow rate from OVTPI to T_s, calculated as the averaged T_s within the red-boxed area in Fig. 1(a), is found to be -0.38 nats/year, surpassing the 90% confidence level. These findings align with the notable impact of OVTP on T_s over the TP during the MJJ period.

In previous studies, a positive land-atmosphere feedback process involving heat waves, cloud cover, the atmospheric boundary layer, and surface sensible heat flux (ISHF) was proposed. To investigate whether there is a positive land-atmosphere feedback that amplifies the impact of OVTP on T_s over the TP, the regression of MJJ surface temperature anomalies, boundary layer height (BLH) anomalies, total cloud cover (TCC) anomalies, and ISHF anomalies against the MJJ OVTPI are plotted (Fig. 6). Corresponding to the strengthening of the OVTP, positive T_s anomalies (Fig. 6a) and BLH anomalies (Fig. 6b) are observed, whereas negative TCC anomalies (Fig. 6c) and ISHF anomalies (Fig. 6d) are identified. Negative TCC anomalies are usually associated with increased shortwave radiation and surface sensible heat flux. These anomalies lead to a deepening of the atmospheric boundary layer, which in turn contributes to a further reduction in TCC. Based on the results from Table 1, OVTPI, T_s, BL, TCC and ISHF exhibit significant correlations with each other over north-
western TP. Consequently, it is evident that the MJJ OVTP exerts a significant influence on $T_s$ over the TP by amplifying its impact through a positive land-atmosphere feedback. This raises the next question: how does the MJJ OVTP affect $T_s$ in the subsequent summer?

Comparing $T_s$ anomaly patterns between the period of MJJ (Fig. 6a) and JJA (Fig. 7a) regressed against MJJ OVTP, the influence of OVTP on the $T_s$ anomaly pattern persists from MJJ to JJA. The land surface temperature anomaly in the TP has been observed and supported by model simulations to persist over seasons\cite{52, 53}. This sustained anomaly is often accompanied by subsurface temperature, snow cover, and surface albedo anomalies\cite{52}. To explore the potential factors contributing to the persistence in this study, a comparison is made between the persistent component of $T_s$ and JJA $T_s$ anomaly regressed against MJJ OVTP. According to Pan (2005), the persistent component of the $T_s$ in JJA, $T_{sp}$, can be calculated as:

$$T_{sp} = T_s(MJJ)\text{Cov}[T_s(JJA), T_s(MJJ)]/\text{Var}[T_s(MJJ)]$$ (1)

The terms Cov and Var in equation (1) denote covariance and variance, respectively. The dominant pattern of the $T_s$ persistent component (Fig. 7b) exhibits minimal changes in comparison to that of the total $T_s$ (Fig. 7a), as indicated by their high pattern correlation coefficient of approximately 0.88. Therefore, the land memory effect should be considered as a critical factor in sustaining the influence of OVTP on the $T_s$ anomaly pattern from MJJ to JJA.
**Numerical experiments**

To verify the impact of the positive anomalous TP $T_s$ induced by OVTPI on the atmospheric circulation in East Asia, a numerical experiment is designed using the linear baroclinic model (LBM). The thermal forcing is distributed within an elliptical region centered at $77^\circ$E, $35^\circ$N, with radiues of $8^\circ$ and $10^\circ$ in the latitudinal and longitudinal directions, respectively. An idealized warming profile with a maximum value of 1 K/day at the 0.75 sigma level (around 400 hPa) is employed to mimic the OVTP-induced diabatic warming effect (Fig. 8b). This experiment is performed with a basic state of the summer climatology. The LBM is integrated for 40 days, and the variables during the last 10 days are averaged to obtain the stabilizing state for further analysis.

Figure 8c-e show the simulated response of the atmospheric circulation over East Asia to the heating forcing over the north-western TP. A positive geopotential height anomaly is induced at upper troposphere over TP, which extends eastward towards the northeastern China (Fig. 8c). Meanwhile, the anti-cyclone system over the northeastern China also occurs at 500 hPa (Fig. 8b). At 850 hPa, the center of the anti-cyclone system is located in the Yangtze-Huaihe River Basin, accompanied by easterly winds along the southeast coast of China (Fig. 8e). The anomalous circulation pattern, which is in good agreement with the observed circulation shown in Fig. 3c, plays a crucial role in generating negative precipitation anomalies in the Yangtze River Basin and positive precipitation anomalies in southern China through the transport of moisture. Overall,
the results from the numerical experiment demonstrate that the heating forcing over the north-western TP acts as a link between the OVTP and precipitation in East Asia.

**DISCUSSIONS**

The depletion of ozone has significant implications for both ecosystems and climate. Previous studies have primarily focused on the causes and climate impacts of polar ozone holes, while the climate impact of the OVTP has received limited attention. In this study, we aim to quantify the contribution of the OVTP during its peak season of MJJ to East Asian summer precipitation. Our findings reveal that the OVTP explains approximately 15% of the variability in summer precipitation in East Asia. Moreover, we identify the $T_s$ anomaly over the TP as a crucial link between the OVTP and East Asian precipitation. Causality analysis confirms that the intensification of MJJ OVTP, characterized by a significant reduction in TCO from 30 to 200 hPa, leads to a notable decrease in stratospheric temperature due to reduced ozone absorption in the UTLS. This, in turn, allows more radiation to reach the troposphere and surface. Additionally, the intensification of MJJ OVTP also leads to a high pressure anomaly near 150 hPa. This anomaly suppresses cloud formation near the surface, leading to an increase in local net shortwave radiation and surface sensible heat flux. Consequently, the atmospheric boundary layer rises, further inhibiting cloud formation. Through this positive land-atmosphere feedback, the surface temperature anomaly over the TP is reinforced. The anomalous surface temperature pattern persists into summer and impacts the precipitation in East Asia by inducing anti-cyclone anomalies at 850 hPa centered over the Yangtze-Huaihe River Basin, accompanied by easterly wind
anomalies along the southeastern coast of China. The anti-cyclone anomalies cause negative precipitation anomalies along the Yangtze River Basin, while the easterly wind anomalies facilitate moisture transport and lead to positive precipitation anomalies in southern China.

Zhang et al. (2022) evaluated the OVTP in Coupled Model Intercomparison Project Phase 6 (CMIP6) Models and found that the seasonal cycles and spatial characteristics of the OVTP are generally well captured by most models. In addition, the CMIP6 models using fully coupled and online stratospheric chemistry schemes can better simulate the OVTP than those without interactive chemistry schemes. To demonstrate the significance of the OVTP to East Asian precipitation, we select multiple CMIP6 models with interactive chemistry, including MRI-ESM2-0, GFDL-ESM4, MIROC-ES2H and MPI-ESM-1-2-HAM. Among these models, there are notable differences in capturing the relationship between MJJ OVTP and JJA TS surface temperature. Specifically, MRI-ESM2-0 and MIROC-ES2H show a similar level of correlation (Cor(OVTP, T_s): 0.54 and 0.5, respectively), while GFDL-ESM4 exhibits a weaker correlation (Cor(OVTP, T_s): 0.23) and MPI-ESM-1-2-HAM shows the lowest correlation (Cor(OVTP, T_s): 0.11). Although the correlations in the models with good performance (MRI-ESM2-0 and MIROC-ES2H) are lower than the observed value (Cor(OVTP, T_s): 0.8), they are still able to simulate a precipitation pattern (Fig. 9b) that exhibits a greater resemblance to the observed one (Fig. 9a) than the other models (Fig. 9c). Based on Fig. 9b, the simulation by MRI-ESM2-0, which exhibits good performance in simulating the relationship between MJJ OVTP and JJA T_s,
successfully reproduces the dry anomalies along the Yangtze River Basin to southern
Japan (Fig. 9b). However, it does not accurately simulate the positive precipitation
anomalies observed in the Indochina Peninsula and southern China region. For models
that fail to accurately capture the MJJ OVTP and JJA T_s, they encounter significant
challenges in simulating the response of East Asian precipitation to the OVTP (Fig. 9c).
Overall, most available models in CMIP6 have a limitation in reproducing the full
strength of the observed relationship between OVTP and East Asian precipitation. This
limitation is likely due to their inability to capture the link between OVTP and TP T_s.
It is crucial to enhance the capability of models to simulate the impacts of OVTP on TP
T_s, which, in turn, would improve their ability to simulate the effect of OVTP on East
Asian precipitation. Given the projections of deepening OVTP in the future as indicated
by most CMIP6 models^{41}, the significance of the OVTP in impacting East Asian
precipitation is expected to become increasingly critical in the coming decades.

METHODS

Reanalysis datasets
The datasets applied in this work include: (1) 1979-2022 monthly TCO, temperature, geopotential height, BLH, TCC, ISHF, horizontal and vertical wind
components gridded at 0.25°×0.25° resolution, available from the European Centre for
ECMWF ERA5 reanalysis^{54}. (2) 1979-2022 monthly precipitation data acquired from
the PREcipitation REConstruction over Ocean (PREC-O) with 2.5°×2.5° grid^{55}. 
Methodology

To demonstrate the causality, a statistical analysis technique, the Liang-Kleeman information flow method is employed. The method relies on a fundamental property that if the evolution of a dynamic event A is not influenced by another event B, then there is no information flow from B to A. Liang (2008) demonstrated that the information flow from \( X_2 \) to \( X_1 \) is given by equation (2):

\[
T_{2 \rightarrow 1} = -E \left( \frac{\partial}{\partial \rho_1} \frac{\partial (F_1 \rho_1)}{\partial x_1} \right) + \frac{1}{2} E \left( \frac{\partial^2 (b_{12}^2 + b_{12}^2) \rho_1}{\partial x_1^2} \right)
\]  

(2)

In this equation, \( \rho_1 \) represents the marginal density of \( X_1 \), \( E \) denotes the mathematical expectation, \( b_{ij} \) and \( F_i \) represent arbitrary functions of \( X_1, X_2 \), and \( t \). For linear systems, Liang (2014) obtained a concise formula for causal analysis between time series, that is:

\[
T_{2 \rightarrow 1} = \frac{C_{11} C_{12} C_{2,d1} - C_{12}^2 C_{1,d1}}{C_{11}^2 C_{22} - C_{11} C_{12}^2}
\]  

(3)

In equation (3), \( C_{ij} \) is the sample covariance between \( X_i \) and \( X_j \), while \( C_{i,dj} \) denotes the covariance between \( X_i \) and \( \dot{X}_j \). Here, \( \dot{X}_j \) represents the difference approximation of \( \frac{dx_j}{dt} \) using the Euler forward scheme:

\[
\dot{X}_{j,n} = \frac{X_{j,n+k} - X_{j,n}}{k \Delta t}
\]  

(4)

Regarding the physical interpretation of \( T_{2 \rightarrow 1} \), the rate of information flow calculated from equation (3), if the value equals to zero, \( X_2 \) does not have a causal influence on \( X_1 \). When the value is negative, it suggests that \( X_2 \) tends to stabilize or enhance the predictability of \( X_1 \). Conversely, the positive value implies that \( X_2 \) tends to make \( X_1 \) more uncertain. Correspondingly, Liang (2014) has provided a method for
testing the significance of information flow. The method has been validated in studying
the relationship between El Niño and the Indian Ocean Dipole (IOD)\textsuperscript{19}.

To investigate the linear response of the circulation anomaly over East Asia to the
TP diabatic heating anomaly, numerical experiments are conducted using the LBM
model. The model is developed based on the dynamical core of the Atmospheric
General Circulation Model (AGCM) and is designed by the Center for Climate System
Research at the University of Tokyo and the National Institute for Environmental
Studies in Japan\textsuperscript{57}. We utilize the dry version of the model with a horizontal resolution
of T42 and 20 vertical sigma levels.

In this study, an OVTP index (OVTP\textsuperscript{I}) is determined by the inverse zonal deviation
of TCO averaged within the TP domain (75°–90°E, 32.5°–42.5°N). Specifically, a
higher OVTP\textsuperscript{I} value indicates a stronger OVTP.

**DATA AVAILABILITY**

The ERA5 data are available from the European Centre for Medium-Range Weather
Forecasts (ECMWF) website (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-
reanalysis-v5). The PREC-O data are obtained from the NOAA website
(https://psl.noaa.gov/data). The CMIP6 models can be downloaded from https://esgf-
node.llnl.gov/search/cmip6/.

**ACKNOWLEDGEMENTS**

This research was jointly supported by the Second Tibetan Plateau Scientific
Expedition and Research (STEP) program (Grant No. 2019QZKK0102), National
Natural Science Foundation of China (NSFC) Major Research Plan on West-Pacific
Earth System Multi-spheric Interactions (project number: 92158203) and NSFC (Grant No. 91937302).

AUTHOR CONTRIBUTIONS

Lingaona Zhu and Zhiwei Wu designed the study. The data collection, data analysis and model designments were performed by Lingaona Zhu. The first draft of the manuscript was written by Lingaona Zhu and all authors reviewed the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.


Table 1 Correlation coefficients among the indices of the OVTPI, $T_s$, BLH, TCC and ISHF for the red-boxed area (70°-95° E, 32.5°-42.5° N) in Fig. 7. The bold italic correlation coefficients exceed the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>OVTPI</th>
<th>$T_s$</th>
<th>BLH</th>
<th>TCC</th>
<th>ISHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVTPI</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_s$</td>
<td>0.80</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLH</td>
<td>0.47</td>
<td>0.37</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCC</td>
<td>-0.50</td>
<td>-0.44</td>
<td>-0.68</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ISHF</td>
<td>-0.61</td>
<td>-0.57</td>
<td>-0.86</td>
<td>0.68</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 1 (a) Long-term mean zonal deviation of the total column ozone (TCO) over the Tibetan Plateau during previous summer (May-June-July, MJJ) for the period 1979-2022. (b) Time series of the normalized OVTP1 defined by the inverse zonal deviation of the TCO averaged in the red-boxed area (70°-95° E, 32.5°-42.5°N) in (a) during MJJ.
Figure 2 (a) JJA precipitation anomalies regressed against the MJJ OVTPI (color shadings; in unit of mm/day). The dotted areas exceed the 95% confidence level. (b) The JJA precipitation fractional variances explained by the MJJ OVTPI (color shadings; in unit of %).
Figure 3 JJA geopotential height anomalies (shading, unit: gpm) and wind anomalies (vector, unit: m/s) regressed against the MJJ OVTP at (a) 200, (b) 500, (c) 850 hPa. The dotted areas and the black vectors exceed the 90 % confidence level.
Figure 4 Vertical-latitude cross sections of MJJ (a) TCO anomalies (shading, unit: DU); (b) temperature anomalies (shading, unit: K); (c) geopotential height anomalies (shading, unit: gpm); (d) cloud cover anomalies (shading, unit: %) regressed against the MJJ OVTPI along 70°-95° E. The dotted areas exceed the 95 % confidence level.
Figure 5 Vertical-latitude cross section of information flow from MJJ OVTP to MJJ (a) temperature and (b) geopotential height (shading, unit: nats/year) along 70°-95° E. The dotted areas exceed the 90% confidence level.
Figure 6 MJJ (a) surface temperature anomalies (shading, unit: K); (b) boundary layer height (BLH) anomalies (shading, unit: m); (c) total cloud cover (TCC) anomalies (shading, unit: %); (d) instantaneous surface sensible heat flux (ISHF) anomalies (shading, unit: J/m$^2$) regressed against the MJJ OVTPI. The dotted areas exceed the 95% confidence level.
Figure 7 JJA (a) $T_s$ anomalies (shading, unit: K) and (b) the persistence component of $T_s$ regressed against MJJ OVTPI. The dotted areas exceed the 95% confidence level.
Figure 8 (a) The spatial pattern of the heating forcing (shading, unit: K/day) at the sigma level of 0.75 and (b) the vertical profile of the heating forcing (black curve, unit: K/day) around the horizontal maximum heating centre (35°N, 77°E). Simulated response of geopotential height (shading, unit: gpm) and wind (vector, unit: m/s) at (c) 200, (d) 500, (e) 850 hPa to the heating forcing added to the climatological summer atmospheric circulation.
Figure 9 JJA precipitation anomalies regressed against the MJJ OVTPI (color shadings; in unit of $10^{-5}$ kg/m$^2$s) of (a) ERA5 TCO and PREC-O precipitation data, (b) CMIP6 model MRI and (c) CMIP6 model HAMMOZ during 1979-2014. The dotted areas exceed the 95% confidence level.