Impact of the Tibetan Plateau on East Asian Summer Monsoon: a Land–Air–Sea Interaction Perspective

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Targeted Training Activity
1. Introduction

2. Relative contribution of the Tibetan Plateau heating and the IOBM

3. Oceanic Forcing on East Asian Summer Monsoon Altered by Tibetan Plateau Heating Effect
Importance of the Tibetan Plateau

Mechanical control in winter

(Yeh, 1950, Tellus)

A strong heat source in summer

(Wu et al., 2012, Sci Rep
An et al., 2015, Annu Rev Earth Planet Sci)
Schematic diagram of the role of TP thermal forcing in the summer climate patterns

\[ \beta \nu + (f + \zeta) \nabla \cdot \vec{V} = 0 \]

(Duan and Wu, Clim. Dyn. 2005)
Interannual variation of EASM precipitation and TP heating

Precipitation difference between strong and weak Tibetan Plateau heating years

EOF1 of East Asian summer rainfall

(Hsu and Liu 2003)
Impact on summer rainfall anomaly in EASM

Strong atmospheric heat source over the TP

Warm advection induces upward motion

Large scale circulation response: Steady wave

Synoptic disturbance for torrential rainfall

Excessive precipitation over the Yangtze and Huaihe River basins

(Wang et al., 2014, Clim. Dyn. 2014)
Content

1. Introduction

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Motivation

• Many external factors are known to have impacts on the interannual variability of the EASM, but the prediction skill of the EASM is still low.

(Zhang and Tao 1998)
• Perhaps one reason is the lack of understanding of the relationships among different contributing factors.

• Some previous studies have attempted to discuss the relative contributions of different factors affecting the Asian monsoon (Yang and Lau 1998; Gong and Ji 1998a, b).

• Nevertheless, the relative contribution of land and ocean to the interannual variability of the EASM in terms of circulation and precipitation anomalies remains unclear.
Impacts of the IOBM on the EASM

Lead–lag correlation between the EASM index (Wang et al. 2008b) and four main ocean indexes of different seasons.
Interannual variability of the EASM

TP thermal forcing

Interaction?

IOBM

Relative Contribution

Contents
The EASM index (Wang et al. 2008), is the simpler version of the PC1 of the interannual variability of the EASM obtained from the MV-EOF. The PC1 of East Asian summer precipitation is also used as PR index.

The leading mode of the MV-EOF of 850 hPa wind, precipitation (shaded) and sea level pressure (contour)

The leading mode of the EOF of East Asian summer precipitation based on APHRODITE
Atmospheric heat source over the Tibetan Plateau

Sensible Heating + Condensation Heating + Radiation Cooling

Station+SRB radiation:
- Eastern TP (1984 → 2007)

JRA-55:
- 1984 → 2007

ERA-Interim:
- 1984 → 2007

NCEP/DOE:
- 1984 → 2007

The whole TP (1979 → 2008)
### Data analysis based on observations

<table>
<thead>
<tr>
<th></th>
<th>IOBM</th>
<th>TP thermal forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation with the EASM index</td>
<td>0.615**</td>
<td>0.415*</td>
</tr>
<tr>
<td>Partial correlation with the EASM index</td>
<td>0.589**</td>
<td>0.361*</td>
</tr>
<tr>
<td>Correlation with the PR index</td>
<td>0.232</td>
<td>0.638**</td>
</tr>
<tr>
<td>Partial correlation with the PR index</td>
<td>0.120</td>
<td>0.618**</td>
</tr>
<tr>
<td>Standard regression coefficient on the EASM index</td>
<td>0.550**</td>
<td>0.292*</td>
</tr>
<tr>
<td>Standard regression coefficient on the PR index</td>
<td>0.094</td>
<td>0.618**</td>
</tr>
</tbody>
</table>

**Partial correlation:**

\[
r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1-r_{13}^2)(1-r_{23}^2)}}
\]

**Standard regression coefficient:**

\[
y = \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_0
\]

\[
b_i = \hat{\beta}_i s_{x_i} / s_y
\]
Data analysis based on Partial Correlations

IOBM/TP-Heating vs. Circulation/Precipitation

200hPa

IOBM

TP-Heating

850hPa

(shaded: precipitation; Black dots indicate 90% significance)
Experiment design

Model: FAMIL version of F/SAMIL, developed by LASG/IAP

Goal: Add 2.5σ of anomaly in both TP Heating and IOBM experiments

Difference of total diabatic heating between “strong years” and “weak years” of the TP thermal forcing

The vertical profile of the standard deviation of the diabatic heating over the eastern TP

The difference of the vertical profile of the diabatic heating between “strong years” and “weak years”

~2.5 times
Red: 1; Yellow: 1/4

Distribution of the condensation heating added into TP HEATING experiments

SST anomalies added into the IOBM_TPctrl and IOBM_TPfree experiments

The standard deviation of the tropical Indian Ocean is 0.2K, so 2.5 times of that is 0.5K
**Experiment design**

**CONTROL** experiment runs for 20 years
The three sensitivity experiments comprise 20 ensembles with different initial conditions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>control</strong></td>
<td>Prescribed global climatological SST/sea ice</td>
</tr>
<tr>
<td><strong>TP heating</strong></td>
<td>Add $2.5 \sigma$ condensation heating profile in the central-eastern TP</td>
</tr>
<tr>
<td>positive</td>
<td></td>
</tr>
<tr>
<td>negative</td>
<td>Remove $2.5 \sigma$ condensation heating profile in the central-eastern TP</td>
</tr>
<tr>
<td><strong>IOBM_TPctrl</strong></td>
<td>Add 0.5 K SST in the tropical Indian Ocean, with prescribed TP condensation heating in control</td>
</tr>
<tr>
<td>positive</td>
<td></td>
</tr>
<tr>
<td>negative</td>
<td>Remove 0.5 K SST in the tropical Indian Ocean, with prescribed TP condensation heating in control</td>
</tr>
<tr>
<td><strong>IOBM_TPfree</strong></td>
<td>Add 0.5 K SST in the tropical Indian Ocean</td>
</tr>
<tr>
<td>positive</td>
<td></td>
</tr>
<tr>
<td>negative</td>
<td>Remove 0.5 K SST in the tropical Indian Ocean</td>
</tr>
</tbody>
</table>
JJA mean 850 hPa circulation and precipitation in FAMIL

Experiment results

Observation

FAMIL

850hPa wind and precipitation (shaded)
Experiment results

200hPa

IOBM_TPctrl

TP-Heating

500hPa

(shaded: precipitation; Black dots indicate 90% significance)

850hPa

C

A
Leading mode of circulation in lower levels

Main rainfall belt of the EASM

Relative Contribution

Interannual variability of the EASM

Relative importance between TP heating and IOBM

TP thermal forcing

IOBM
Impacts of the IOBM on the TP Heating

Correlation between IOBM and circulation/Prec.

Observation

Experiment Results

(a) 200hPa

(b) Surface

Black dots indicate 90% significance

(a) IOBM_TPfree 200hPa

(b) IOBM_TPfree surface
Impacts of the IOBM on the TP Heating

Stronger thermal forcing in the southeastern TP

TP thermal forcing

Warmer Indian Ocean

IOBM

Interannual variability of the EASM
TP-Heating experiment based on FAMIL-OMLM

SST difference and 850 hPa circulation

JJA SST standard deviation

shading: Prec.
TP-Heating experiment: Surface heat fluxes

- Sensible heating
- Latent heating
- Net shortwave
- Net longwave
- Cloud amount

(dotting: 90% confidence level)
Leading mode of circulation in lower layers

Main rainfall belt of the EASM

Relative Contribution

Interannual variability of the EASM

Stronger thermal forcing in the Eastern TP

Warmer Indian Ocean

TP thermal forcing

IOBM

Conclusion
The relative contributions may change month by month in the summer.

The other modes of IAV in EASM need a further study.

The interaction between the TP thermal heating and the IOBM and the impacts of their interaction on the EASM should be investigated by using a fully air–sea coupled general circulation model.

Factors impacting on the EASM in the leading seasons need to be considered. (ENSO, ENSO Modoki, IOD, Snow cover/depth over the TP/Eurasia).

The story might be different in other time scales.
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Background & motivation

Background

• East Asian summer monsoon (EASM): strong interannual variability (IAV) (e.g. Yang and Lau 2006; Zhou et al. 2010).

• The IAV of EASM is determined by the combination effect of the Pacific and Indian Oceans (Wang et al. 2000, 2006), the thermal forcing over the Tibetan Plateau (TP) (Zhao and Chen 2001; Duan et al. 2005; Wang et al. 2014), as well as the mid-latitudes atmospheric internal dynamics (He et al. 2016).

• The leading mode of the global SSTA (quasi-quadrennial oscillation, QQO) has significant impacts on the East Asian climatic anomalies (Liu and Duan 2017).

Motivation

• Responses of EASM to the global SSTA in different phase of the QQO?

• Relative contributions of the direct effects of the global SSTA and the thermal feedback of TP heating?

• How the SSTA impact the anomalous TP heating?
EASM and climate natural variability

Circulation
(Wang et al., 2008)

Precipitation
(EOF1 of Pr)
• **Station observation**: 73 stations over the Tibetan Plateau

• **SST data**: HadISST1, 1° × 1° (*Rayner et al. 2003*)

• **Reanalysis datasets**: ERA-Interim, 1° × 1°, 37 pressure levels (Dee et al. 2011); JRA-55, 1.25° × 1.25°, 37 pressure levels (*Ebita et al. 2011*)

• **Precipitation data**: GPCP version 2.1, 2.5° × 2.5° (*Adler et al. 2003*)

• The temporal coverage is from **1979 to 2013** and the long-term linear trend is removed.
“Principal Oscillation Pattern (POP)” (Hasselmann 1988; Penland 1989; von Storch et al. 1995)

\[ x(t + 1) = A \cdot x(t) + \text{noise} \]  \hspace{1cm} (1)

\[ A = E \left[ x(t+1)x^T(t) \right] \cdot \left[ E \left[ x(t)x^T(t) \right] \right]^{-1} \]  \hspace{1cm} (2)

A pair of conjugate eigenvectors of Eq. (2), \( p_k = p_k^r + ip_k^i \) and \( p_k^* = p_k^r + ip_k^i \), are called the principal oscillation patterns (POPs) or the normal modes of Eq. (1).

In a cycle, the evolution of the POPs is

\[ \cdots \rightarrow p_k^i \rightarrow p_k^r \rightarrow -p_k^i \rightarrow -p_k^r \rightarrow p_k^i \rightarrow \cdots \]  \hspace{1cm} (3)

**Evaluation indicators of the POPs of the global SSTA during 1979-2013**

<table>
<thead>
<tr>
<th>NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (month)</td>
<td>45.701</td>
<td>28.872</td>
<td>102.241</td>
<td>52.571</td>
<td>226.445</td>
<td>69.392</td>
<td>155.577</td>
<td>1648.545</td>
</tr>
<tr>
<td>Biasing factor</td>
<td>0.534</td>
<td>0.511</td>
<td>0.436</td>
<td>0.367</td>
<td>0.341</td>
<td>0.336</td>
<td>0.326</td>
<td>0.324</td>
</tr>
</tbody>
</table>
Quasi-quadrennial Oscillation mode (QQOM) of global SSTA

Developing phases: cold IOBM $\rightarrow$ IOD + developing El Niño

Decaying phases: warm IOBM persist + decaying El Niño

The leading mode of the global SSTA: quasi-quadrennial oscillation (QQOM) \cite{Liu:2017}

\cite{Liu:2017}
Explained variance of the QQOM

(a) POP - Variance Ratio Percent

SST - %

[Map showing explained variance of the QQOM with color-coded regions indicating the variance ratio percent.]
Methods: phase composite analysis

The reconstructed component can be written as

\[ \hat{x}(t) = z_r(t)p_r + z_i(t)p_i \]

The phase angle is \( \theta = \arctan\left(\frac{z_r}{z_i}\right), \theta \in [-\pi, \pi) \)

Criterion: both of the phase angles in spring and summer of the current year are within the current phase and the absolute value of the real part of POP time coefficient exceeds 0.4 standard deviations

**Years for phase composite analysis in summer**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Year</th>
</tr>
</thead>
</table>
Methods: **AGCM numerical simulation**

**AGCM:** FAMIL developed by LASG/IAP

<table>
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<th>Experiment</th>
<th>Design</th>
<th>Number of ensembles (Integration length for each)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMIP2</td>
<td>Global SST/sea ice prescribed by AMIP2 from 1979 to 2009</td>
<td>1 (31 years)</td>
</tr>
<tr>
<td>CLIMA</td>
<td>Annual periodic climatological monthly SST/sea ice</td>
<td>1 (20 years)</td>
</tr>
<tr>
<td>TP_FREE</td>
<td>Addition of the ideal quadrennial POPs of the global SSTA with <strong>freeing the TP heating</strong></td>
<td>4 (20 years)</td>
</tr>
<tr>
<td>TP_CTL</td>
<td>Addition of the ideal quadrennial POPs of the global SSTA with <strong>controlling the TP heating</strong></td>
<td>4 (20 years)</td>
</tr>
</tbody>
</table>

The prescribed TP heating is derived from the climatological mean of the tendency of temperature in the modules of cloud microphysical processes, cumulus convection processes, and boundary layer processes in CLIMA experiment.
Response of EASM to the observed SSTA

OBS

UV200

UV500

Pr

-Div(qU, qV)
Response of EASM in AGCM (850 hPa circulation and Pr) (Difference between positive and negative phases of QQOM)

- IOD El Niño developing
- Negative TP heating
- Cyclonic anomaly over Phillipine Sea
- Warm IOBM decaying El Niño
- Dipole pattern over East Asia
- Enhanced main rainfall belt
Response of TP heating

OBS

Released latent heating (dominant)

Surface sensible heating

Radiation cooling
Response of TP heating

Released latent heating + Surface sensible heating

(1) Positive developing

(2) Positive decaying

OBS

AGCM
During the developing stage of the positive phase of QQOM, the significant negative anomaly of the diabatic heating over the TP will induce a cyclonic anomaly over the Phyllipine Sea.
Anomaly of TP heating

Why the TP heating weakens?

UV200

UV500

Pr

Div(qU, qV)
Response to the global SSTA POP: developing year summer
Normalized anomalies of circulations at 200 hPa and SSTAs in summer of the developing year during the QQQ positive phase of the global SSTA. (a) composite analysis for the observational anomalies; (b) normalized difference in the numerical simulations between the sensitive experiment TP_FREE and the control experiment CLIM. Black vectors denote the horizontal wind, contours denote the geopotential height (red is positive; black is zero; blue is negative; interval is 0.3), and shading denotes the SSTA. The SSTA in (b) is prescribed in the experimental design.
Composite analysis for the observational wave activity in summer of the developing year during the QQOM positive phase of the global SSTA. Contours denote the geopotential height (units: gpm; red: positive; black: zero; blue: negative; interval: 10 gpm), black vectors and shading denote the horizontal components of wave activity flux (units: m$^2$s$^{-2}$) and their divergence (units: ms$^{-2}$).
Conclusions

- The remarkable precipitation anomaly of the EASM with the enhanced main rainfall belt occurs in the positive decaying years of the QQOM, corresponding to the enhanced and the westward-extended WPSH and the accelerated subtropical westerly jet in the upper troposphere.

- The significant response of the summer TP heating, featured by the suppressed in situ atmospheric heat source and deficient precipitation, can be detected only in the positive developing years of the QQOM. The weakened TP heating feedback rather than the direct SSTA effects plays a dominant role on the formation of the anomalous Philippine Sea cyclone.

- Both the wave trains from Atlantic and the upper-level southwesterly wind contributes the weaken TP heating in the positive developing years of QQOM.


Thank you for your attention!
Observed Data Analysis

Time series of the standard anomalies of the MAM SHTP and MAM Niño3.4 index with the linear trend excluded. Note that the correlation coefficient between SHTP and Niño3.4 index was only 0.21 (below the 90% significance level), indicating that SHTP is independent of ENSO.

A weak positive correlation exists between spring TPSH and ENSO, hence we use partial regression to separate their relative contributions.
Above-normal spring SHTP induces a weak spring WPSH, but a strong summer WPSH, and vice versa. In particular, SHTP acts as an independent factor for the WPSH anomaly relative to ENSO events.