Isolated Tropical Indo-Pacific SSTA Impacts on ISMR Variability in Observations and CMIP6 Historical Simulations

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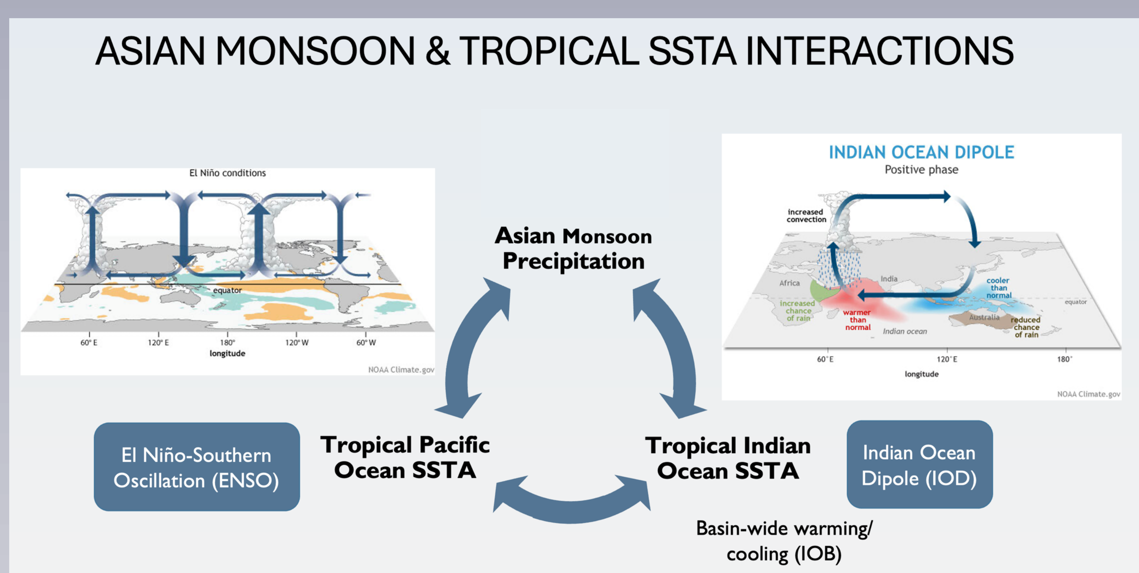
Background & Motivation

The Asian Summer monsoon occurs each year from June-September and brings essential precipitation to one of the most densely populated regions in the world.



The purpose of this study is to identify individual model biases in the CMIP6 historical simulations associated with the impacts of tropical Pacific and Indian Ocean SSTAs on Indian summer monsoon rainfall variability

Methods I: Linear Inverse Model (LIM)

Evolution of a state vector, $\boldsymbol{x}$:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{L}\boldsymbol{x} + \xi \quad [1]$$

$\boldsymbol{L}$ = linear dynamical operator
ξ = noise forcing

For the cyclo-stationary LIM (CS-LIM) [2],

$$\boldsymbol{L}_j = \frac{1}{\tau_0}\ln\left[\boldsymbol{C}_j(\tau_0)\boldsymbol{C}_j(0)^{-1}\right] \quad \text{for } j = 1, 2, \ldots, 12$$

Noise forcing (ξ) is generated based on the eigenanalysis of $\boldsymbol{Q}$:

$$\boldsymbol{Q}_j = \frac{\boldsymbol{C}_{j+1}(0) - \boldsymbol{C}_{j-1}(0)}{2\Delta t} - \left[\boldsymbol{L}_j\,\boldsymbol{C}_j(0) + \boldsymbol{C}_j(0)\boldsymbol{L}_j^{\,T}\right] \quad \text{for } j = 1, 2, \ldots, 12$$

State vector can be separated into an Indian Monsoon ($\boldsymbol{x_M}$), tropical Pacific ($\boldsymbol{x_P}$), and tropical Indian Ocean ($\boldsymbol{x_I}$) component:

$$\frac{d\boldsymbol{x}}{dt} = \frac{d}{dt}\begin{bmatrix}\boldsymbol{x}_M \\ \boldsymbol{x}_P \\ \boldsymbol{x}_I\end{bmatrix} = \begin{bmatrix}\boldsymbol{L}_{MM} & \boldsymbol{L}_{MP} & \boldsymbol{L}_{MI} \\ \boldsymbol{L}_{PM} & \boldsymbol{L}_{PP} & \boldsymbol{L}_{PI} \\ \boldsymbol{L}_{IM} & \boldsymbol{L}_{IP} & \boldsymbol{L}_{II}\end{bmatrix}\begin{bmatrix}\boldsymbol{x}_M \\ \boldsymbol{x}_P \\ \boldsymbol{x}_I\end{bmatrix} + \begin{bmatrix}\xi_M \\ \xi_P \\ \xi_I\end{bmatrix}$$

$$\frac{d\boldsymbol{x}_M}{dt} = \boldsymbol{L}_{MM}\boldsymbol{x}_M + \boldsymbol{L}_{MP}\boldsymbol{x}_P + \boldsymbol{L}_{MI}\boldsymbol{x}_I + \xi_M$$

$$\frac{d\boldsymbol{x}_P}{dt} = \boldsymbol{L}_{PM}\boldsymbol{x}_M + \boldsymbol{L}_{PP}\boldsymbol{x}_P + \boldsymbol{L}_{PI}\boldsymbol{x}_I + \xi_P$$

$$\frac{d\boldsymbol{x}_I}{dt} = \boldsymbol{L}_{IM}\boldsymbol{x}_M + \boldsymbol{L}_{IP}\boldsymbol{x}_P + \boldsymbol{L}_{II}\boldsymbol{x}_I + \xi_I$$

LIM Process Experiment	Removed Forcing Term(s)	Description
Full-LIM	none	Includes all interactions between tropical Pacific SSTAs, tropical Indian Ocean SSTAs, and Indian monsoon precipitation anomalies.
No P→M	$\mathbf{L}_{MP} = 0$	Direct impacts from tropical Pacific Ocean SSTAs onto Indian monsoon precipitation anomalies is removed.
No I→M	$\mathbf{L}_{MI} = 0$	Direct impacts from tropical Indian Ocean SSTAs onto Indian monsoon precipitation anomalies is removed.
No P↔I	$\mathbf{L}_{IP} = \mathbf{L}_{PI} = 0$	Interaction between tropical Pacific and Indian Ocean SSTAs is removed.

Methods II: Application of LIM

We applied a CS-LIM to monthly observations of precipitation (GPCC[3]) and SST (HadISST[4] and ERSSTv5[5]) and the output from the historical simulations of 7 different CMIP6[6] models from 1950-2014.

CMIP6 Model Name	Modeling Center, Country	Horizontal Resolution (lat. × lon.)	# of Ensemble Members	# of Stable LIM Ensemble Members
E3SM-2-0	DOE, USA	1° × 1°	21	18
CESM2	NCAR, USA	0.9° × 1.25°	50	9
MIROC6	JAMSTEC, Japan	1.4° × 1.4°	50	11
ACCESS-ESM1-5	CSIRO, Australia	1.25° × 1.9°	40	15
MPI-ESM1-2-LR	MPI, Germany	1.9° × 1.9°	43	18
IPSL-CM6A-LR	IPSL, France	1.26° × 2.5°	32	28
CanESM5-1	CCCma, Canada	2.8° × 2.8°	50	25

For each stable ensemble member (determined following [2]), we computed the LIM state vector from the leading PCs of Indian monsoon precipitation anomalies (60°-95°E, 5°-35°N), tropical Pacific SSTAs (130°E-70°W, 25°S-25°N), and tropical Indian Ocean SSTAs (35°-115°E, 25°S-25°N). For each component of the state vector, all PCs that explained over 2% of the observed or modeled variance were included in the state vector (Fig. 1). Each LIM experiment was run forward in time for 65,000 years for observations and 6,500 years for each stable CMIP6 ensemble member.

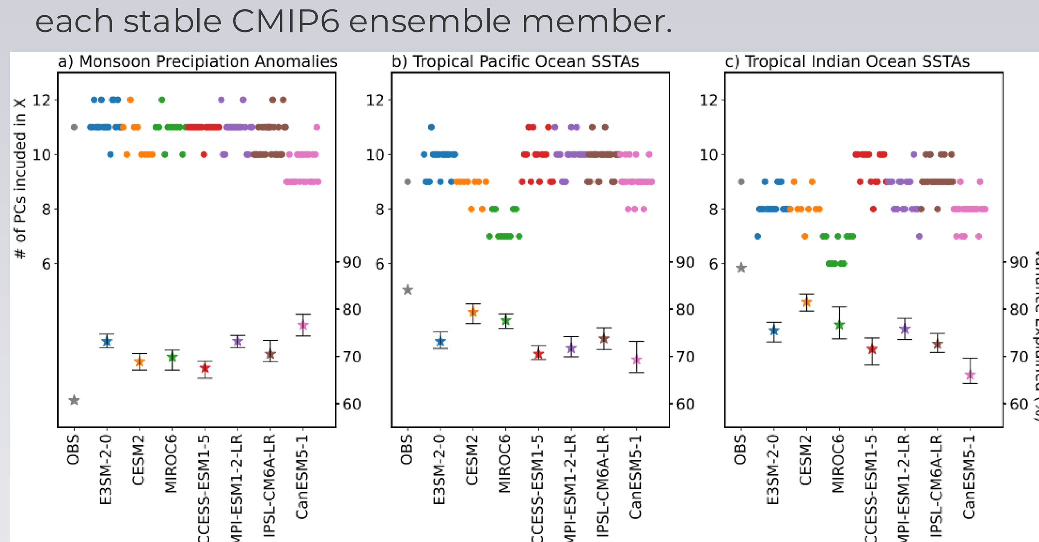


Fig. 1. The number of PCs included in the (a) Indian monsoon precipitation, (b) tropical Pacific, and (c) Indian Ocean SSTA component of the state vector for observations and for each stable ensemble member of the CMIP6 historical simulations (colored circles; left y-axis) and the total amount of observed or modeled variance explained by the included PCs (colored stars; right y-axis). For the CMIP6 models, the star indicates the ensemble mean while the error bars show the minimum and maximum explained variance for each model.

Results I: ISMR Variability

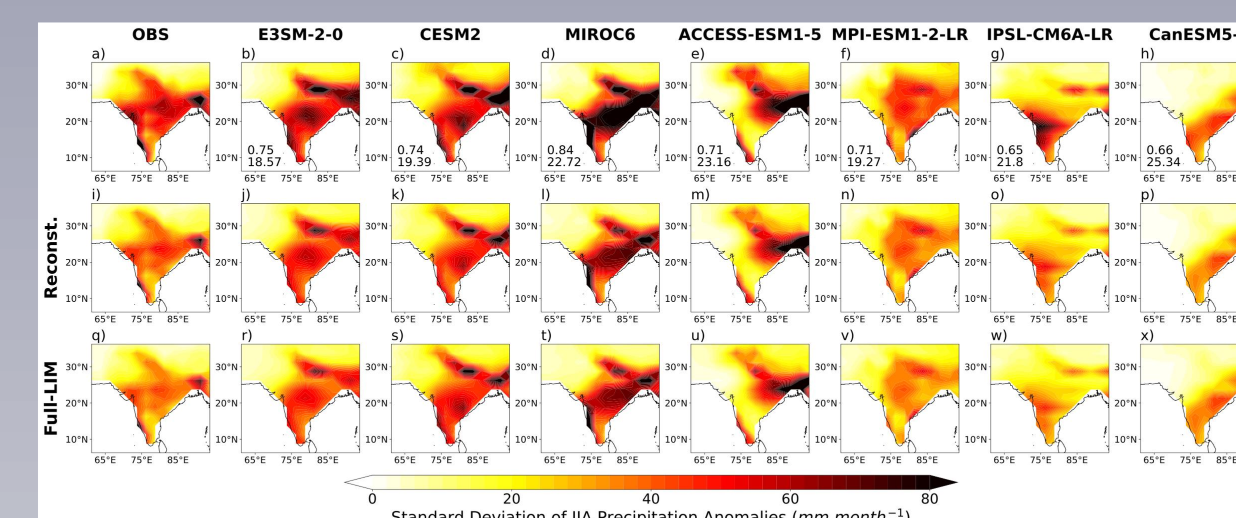


Fig. 2. (a) Observed and (b)-(h) ensemble mean CMIP6 historical standard deviation of JJA precipitation anomalies over India from 1950-2014. (i)-(p) As in (a)-(h), but for the reconstructed precipitation anomalies from the truncated LIM PCs. (q)-(x) As in (a)-(h), but for the *Full-LIM* ensemble mean predicted precipitation anomalies. The correlation (top) and RMSE (bottom) between the observed pattern and each CMIP6 model are shown in the lower left corner for (b)-(h).

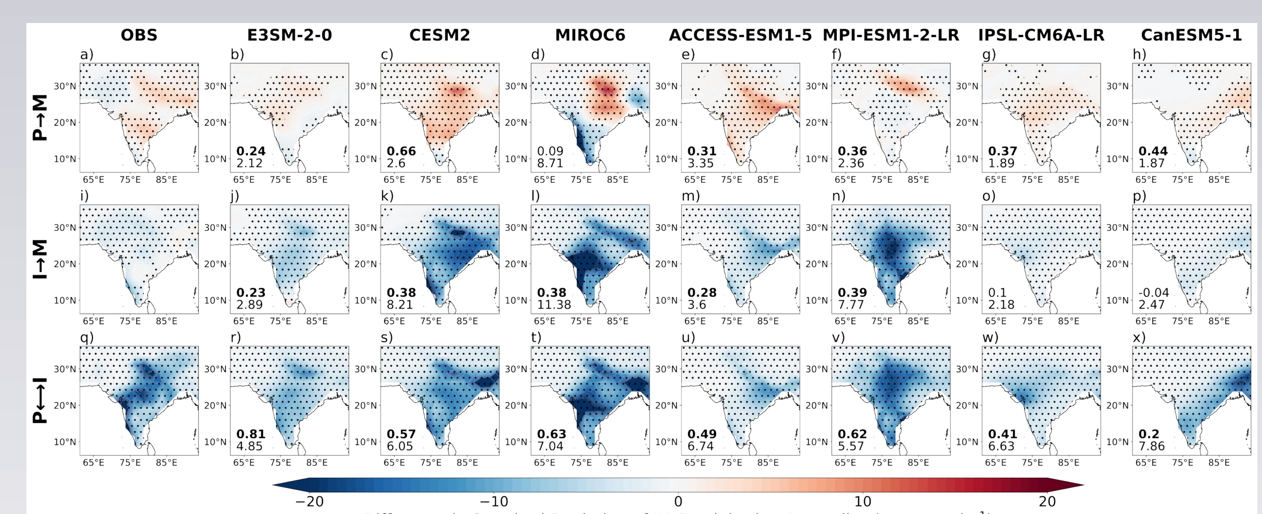


Fig. 3. Difference in the standard deviation of JJA precipitation anomalies over India between the *Full-LIM* and each process experiment for the isolated impacts of (a)-(h) Pacific SSTAs (P→M); (i)-(p) Indian Ocean SSTAs (I→M); and (q)-(x) the Indo-Pacific SSTA interaction (P↔I). Stippling indicates the difference in standard deviation is significant at the 99% confidence level.

Results II: ENSO & IOD Impacts

Guderian et al. (2024) found that the enhanced ISMR variability due to Pacific SSTAs and reduced variability due to Indian Ocean SSTAs and the Indo-Pacific interaction can be partially explained by the counteracting impacts of these forcings on ISMR during ENSO and IOD events. Therefore, we further analyzed the performance of CMIP6 models in capturing the isolated tropical Pacific and Indian Ocean SSTA impacts on ISMR during pure and co-occurring El Niño and positive IOD events.

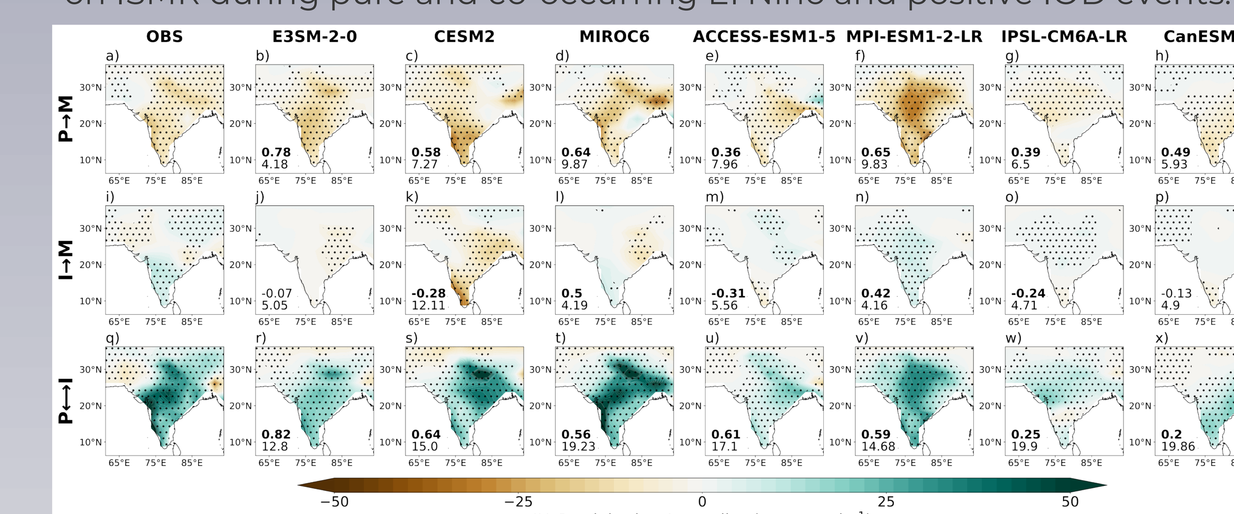


Fig. 4. Composite patterns of ISMR anomalies during developing pure El Niño events for the isolated impacts of (a)-(h) Pacific SSTAs (P→M), (i)-(p) Indian Ocean SSTAs (I→M), and (q)-(x) the Indo-Pacific SSTA interaction (P↔I) in observations and each CMIP6 model. Stippling indicates the difference in composite anomalies is significant at the 95% confidence level.

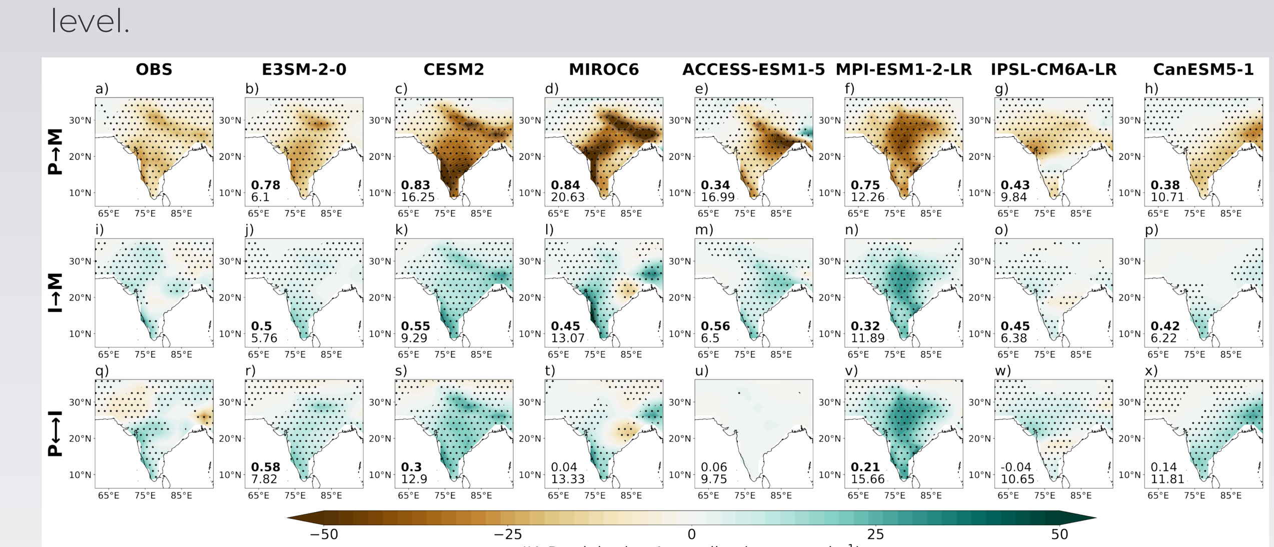


Fig. 5. As in Fig. 4, but for the developing summer of co-occurring El Niño and positive IOD events.

** Pattern correlations (top) and RMSE (bottom) are shown in the lower left corner (significant correlations at 95% confidence level are indicated in bold)*

Summary & Conclusions

We applied a CS-LIM to the historical simulations of seven CMIP6 large ensembles to assess the individual model biases associated with the isolated impacts of tropical Pacific SSTAs, Indian Ocean SSTAs and their interaction on ISMR variability.

- CMIP6 models reproduced the observed enhanced (reduced) ISMR variability from Pacific SSTAs (Indian Ocean SSTAs and the Indo-Pacific interaction), but with varying spatial patterns and magnitudes
  - CESM2 and E3SM-2-0 showed the best agreement with the observed impacts from Pacific SSTAs and the Indo-Pacific interaction, respectively
  - All models had relatively weak correlations with the observed pattern of impacts from Indian Ocean SSTAs
- Composite analysis of ISMR anomalies during developing pure El Niño and co-occurring El Niño and positive IOD events revealed that the impacts of tropical Pacific SSTAs were simulated well by E3SM-2-0, CESM2, MIROC6, and MPI-ESM1-2-LR
  - E3SM-2-0 also showed the best agreement with observations for the effects of the Indo-Pacific SSTA interaction
  - All models showed substantial biases in simulating the Indian Ocean SSTA impacts on ISMR, especially for pure El Niño events
  - Only some models captured observed impacts of Indo-Pacific interaction during co-occurring El Niño and positive IOD events

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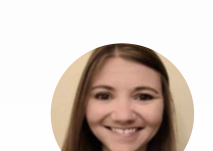

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