

ENSO-Driven Shifts in Monsoon Low-Pressure System Tracks over India in an idealised GCM



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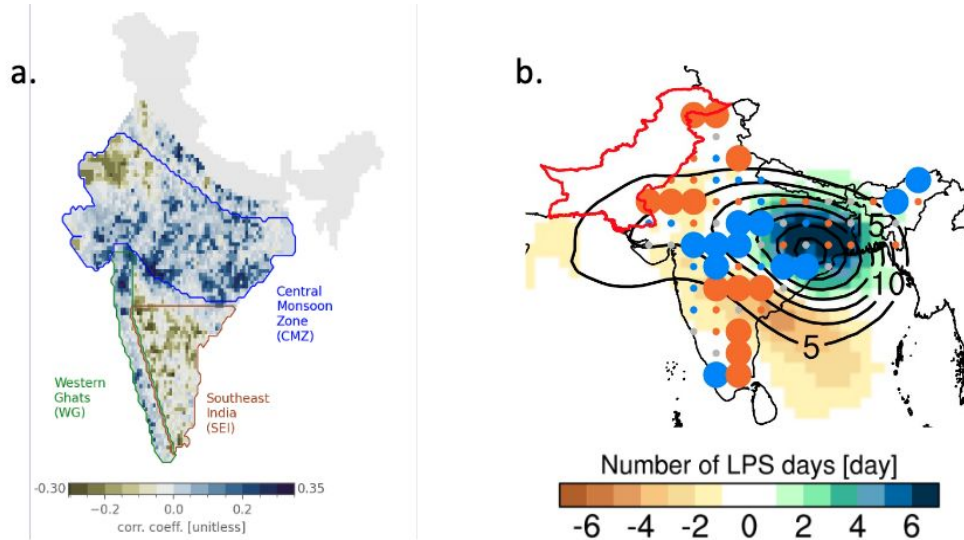
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Introduction or Motivation

- The South Asian summer monsoon is major source of India's annual rainfall, sustaining agriculture and water resources.
- El Niño reduces seasonal-mean rainfall but produces contrasting regional rainfall responses.
- Northwest and southeast India become drier across the entire rainfall distribution.
- Central Monsoon Zone and Western Ghats experience greater variability, with more dry days interspersed with more intense rainfall events (Hill et al., 2025).
- An emerging explanation for this paradox lies in the behavior of monsoon low-pressure systems (LPSs), (Hill et. al. 2025).
- Preliminary ERA5 analysis indicates a northward shift in LPS tracks during El Niño, redistributing LPS-associated rainfall.
- We plan to investigate the physical mechanisms linking ENSO, LPS behavior, and regional rainfall extremes.
- Aim to combine observations and idealized experiments, and comprehensive climate models to assess these mechanisms and their response to warming.



How well do idealized GCMs represent LPSs, LPS tracks and genesis density, distribution of extremes and their connection with the ENSO?

Objectives

- Establish a realistic monsoon mean state that supports LPS-like variability in the simplest model configuration.
- Assess simulated LPS genesis, tracks, and associated rainfall extremes against observations.
- Characterize the three-dimensional structure of simulated LPSs.

Model Framework

Model Framework: ISCA (Clark et. al. 2020, Frierson et al 2006, 2007, Frierson 2007b baseline)

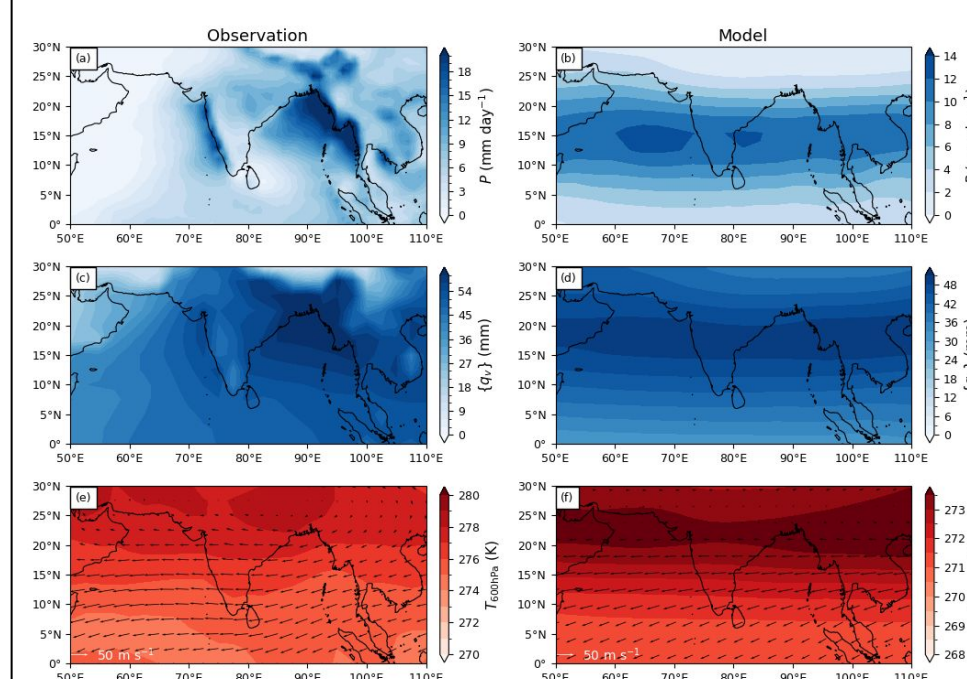
- Dynamics and resolution:** Spectral primitive-equation dynamical core with 40 vertical levels; simulations at T42 (~2.8°) and T85 (~1.4°) assess resolution sensitivity.
- Surface configuration:** Idealized land-ocean distribution, bucket hydrology over land, and mixed-layer depths of 1 m over land and 10 m over ocean to strengthen monsoon temperature and moisture gradients.
- Model physics:** Full-physics RRTMG radiation and Simple Betts-Miller convection scheme.
- Integration and output:** 20-year simulations, with the first 10 years discarded as spin-up; 6-hourly output and daily fields used for analysis.
- Analysis domain and season:** JASO over the South Asian monsoon region (50°–110°E, 5°–25°N).

Methods

- Spectral filtering and regression:** Westward propagating precipitation disturbances isolated within 3–14-day periods and zonal wavenumbers 3–15.
- Event-based tracking:** *TempestExtremes* identified and linked 850-hPa relative vorticity maxima using displacement, gap, duration, and humidity criteria. System diagnostics included minimum MSLP, maximum near-surface wind speed, area-averaged relative humidity, ACE, PDI, and IKE.

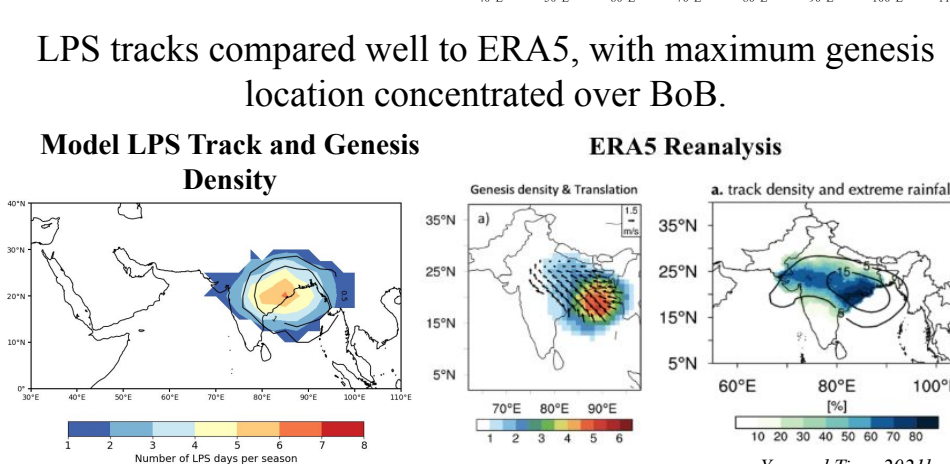
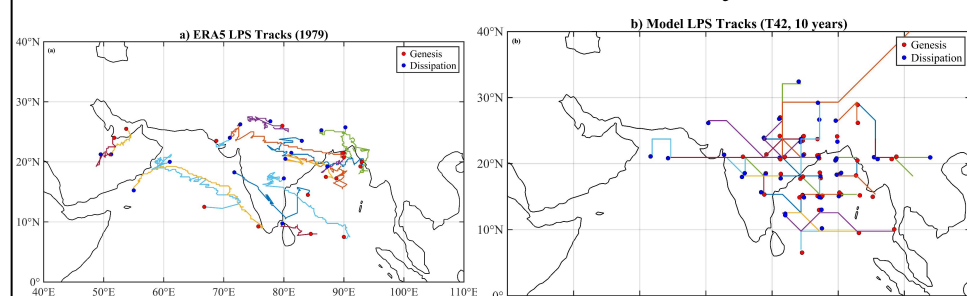
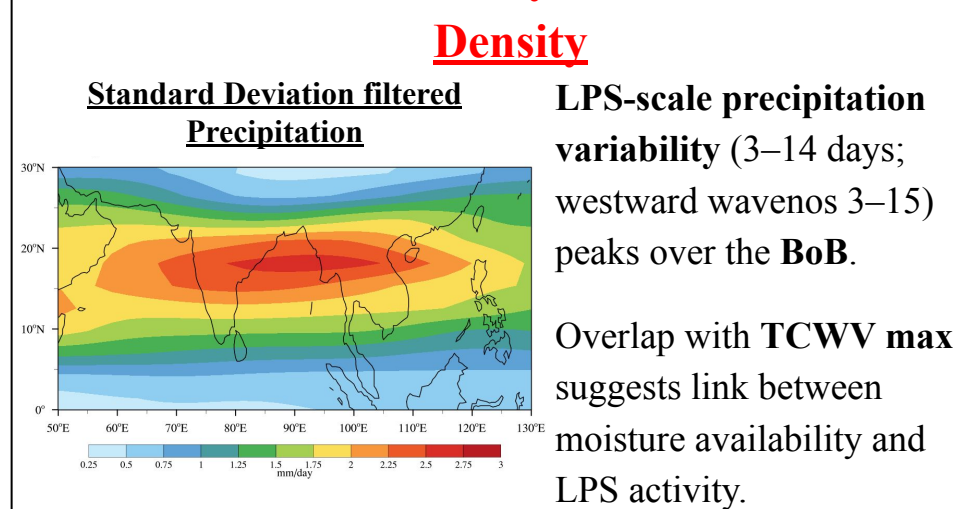
Results

Mean State Climate



- Precipitation:** JASO mean precipitation captures the major monsoon rainfall features, including a maximum over the Bay of Bengal around 15°N, with magnitudes close to reanalysis values.
- Total Column Water Vapor:** The strong meridional moisture gradient provides a favorable background state for moisture-vortex instability and the maintenance of LPSs.
- Temperature and vertical shear:** The meridional temperature gradients and in the BoB region and vertical wind shear indicates a dynamically consistent monsoon mean state, favorable for LPS growth and maintenance.

Simulated LPS Activity, Tracks, and Track Density



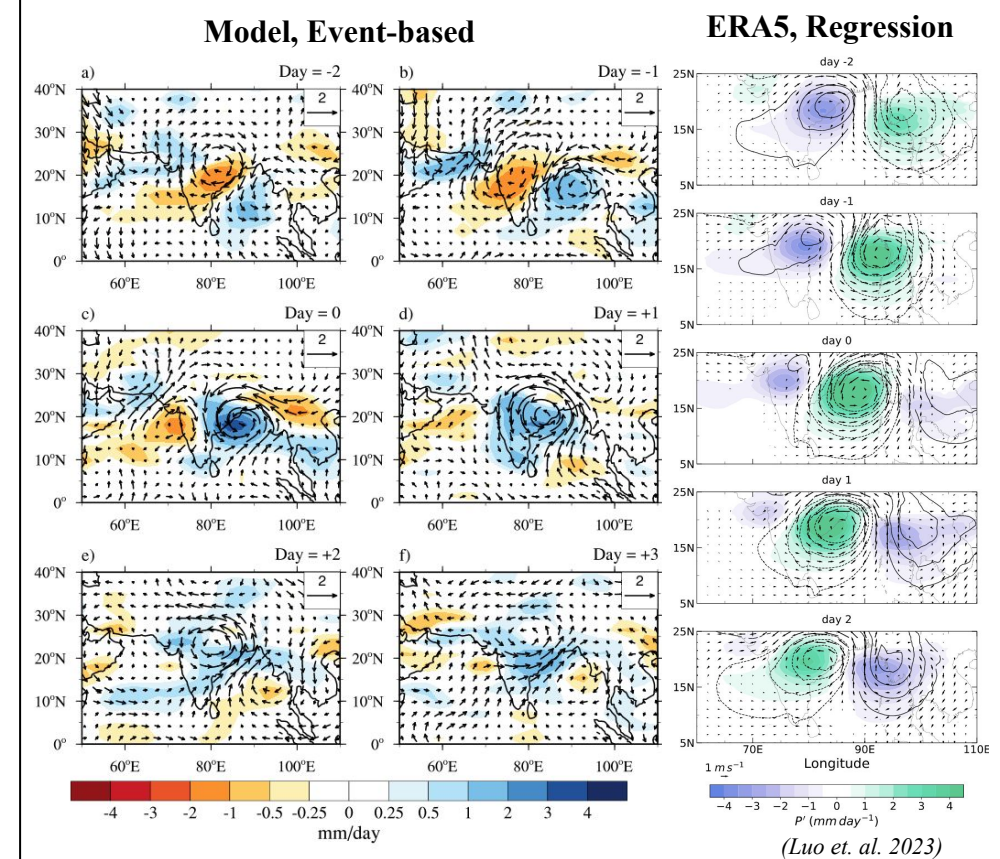
Left plot - Line contour : Genesis density, Shading : Track density

Despite the simple model setup, the distribution of track and genesis densities are in good agreement with that for ERA5 reanalysis dataset.

Results

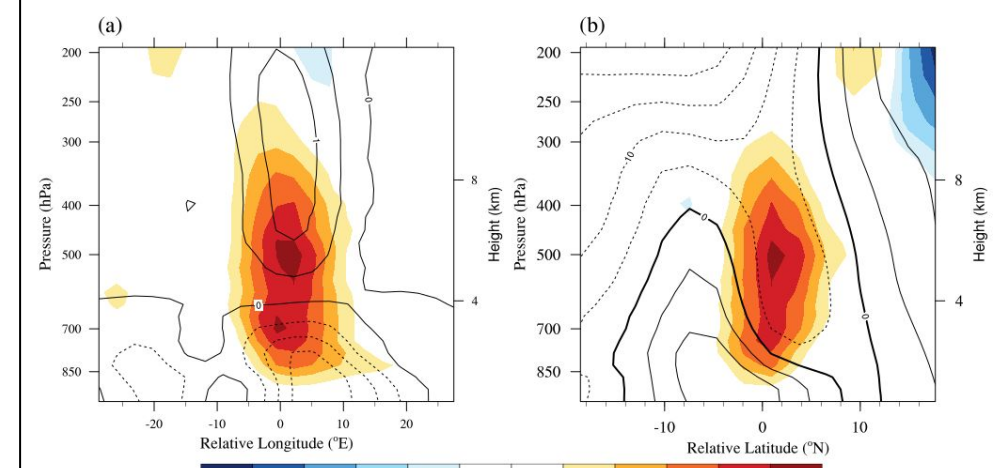
Three dimensional structure of simulated LPSs

Horizontal Structure



- Model captures the horizontal structure of LPSs well.
- LPSs show the expected **north-westward propagation**.
- Precipitation anomalies peaks southwest** of the LPSs storm center.

Pressure vs Lon



Press versus lon plot (17.5°N)
Shading - Ertel PV anomalies (PVU)
line contours - Temperature anomalies

- Warm over cold core structure
- Negligible tilt with height in EPV anomalies
- westerly mean in the lower troposphere
- easterly mean in the mid-upper troposphere

Key Findings and Next Steps

- A simple model captures the essential monsoon environment:** realistic rainfall, moisture and temperature gradients, and vertical wind shear emerge without topography or ocean heat transport.
- LPS variability emerges in the right place with coherent dynamics:** Bay of Bengal activity aligns with the moisture maximum and reproduces the observed convection-circulation relationship, consistent with moisture-vortex instability.
- Realistic storms emerge from simplified physics:** tracked LPSs reproduce observed genesis, propagation, speed, and three-dimensional vortex structure, establishing a strong baseline for targeted sensitivity experiments.

On-going Analysis : Impose ENSO-specific SST and/or Q-flux profiles to identify the mechanisms driving observed shifts in LPS tracks and associated rainfall extremes.

References

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