Biases in model simulations of Indian Summer monsoon low-pressure systems

Mahendra Singh[1], Govindasamy Bala[1,2], and Ashwin K. Seshadri[1,3]

[1]Centre for Atmospheric and Oceanic Sciences (CAOS), Indian Institute of Science Bangalore, Bengaluru, India.
[2]Interdisciplinary Centre for Water Research (ICWaR), Indian Institute of Science Bangalore, Bengaluru, India.
[3]Divecha Centre For Climate Change (DCCC), Indian Institute of Science Bangalore, Bengaluru, India.

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1. Motivation and Research Objective

- Low-pressure systems (LPSs) play a dominant role in driving rainfall over central India during the monsoon season.
- LPSs contribute ~60–70% of monsoon rainfall in northern, central, and eastern India, and their frequency is linked to interannual rainfall variability.
- CMIP climate models exhibit a persistent dry bias over the monsoon core zone, often associated with a southward shift in LPS activity.
- Despite several studies, a detailed mechanistic understanding of the source of biases in LPS characteristics is still lacking.
- Improved representation of LPSs is essential for better seasonal predictions and future projections of monsoon rainfall.

Research Objective:

- To evaluate the simulation of monsoon LPS characteristics—frequency, intensity, genesis, and tracks—in the CESM2.1.3 model.
- To contribute toward a mechanistic understanding of model biases in simulating LPSs within the broader context of ISM simulations.

2. Methods, Models, and Data Used

a. LPS Tracking

- LPSs are tracked using a validated algorithm (Thomas et al. 2021) based on 850hPa geopotential height anomaly and relative vorticity, applied to CESM and reanalysis datasets.

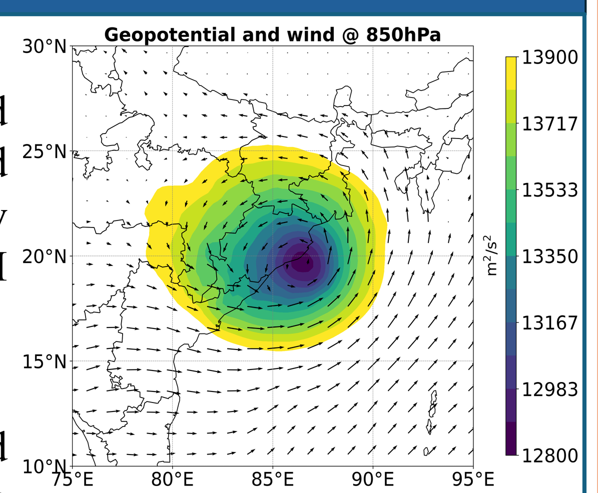

Figure-1: Snapshot of geopotential (shaded, in m^2/s^2) and wind vectors at 850 hPa for a monsoon low-pressure system (LPS) on 28 June 2007 at 18:00 IST.

b. Earth System Model Configuration

- Simulations use the fully coupled CESM2.1.3 (CAM6–CLM5–POP2) in B1850 compset with year-2000 boundary conditions.
- A 119-year CTRL simulation at 0.9°×1.25° resolution is analyzed, focusing on the last 33 years after spin-up using six-hourly output.

c. Other Datasets

- ERA5 (1979–2015), ERA-Interim (1979–2015), NCEP (1965–2005), and MERRA-2 (1980–2005) reanalyses are used for validation and bias estimation; all datasets are re-gridded to CESM resolution.
- CMIP5 (1965–2005) and CMIP6 (1965–2005) historical simulations used for model comparison (CMIP5; MDs track data sourced from Rastogi et al. 2018).

3. Bias in LPS activity and ISM Rainfall

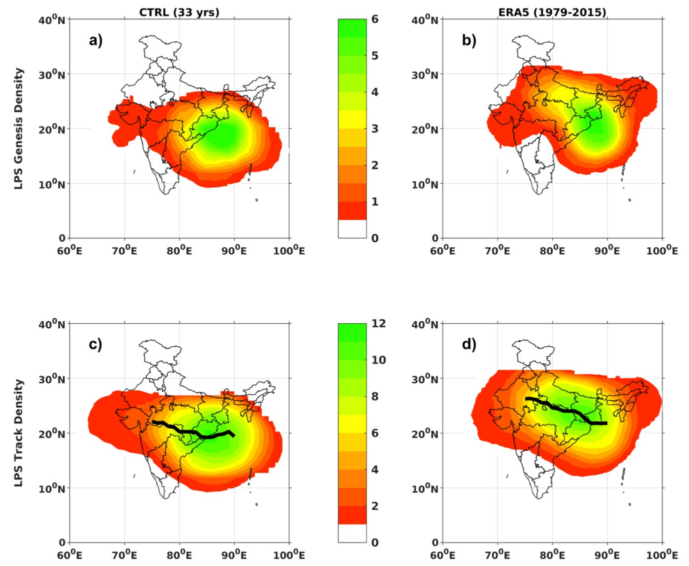

Figure-2: LPS (a, b) genesis densities and (c, d) track densities, showing the number of genesis locations or the number of tracks per year passing within a 500 km radius of each location.

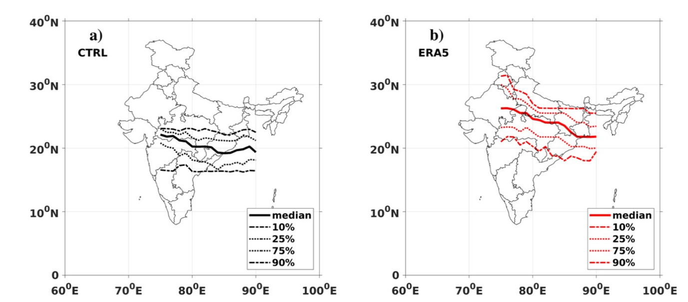

Figure-3: LPS median track (solid line), with 10% of the tracks falling north (south) of the upper (lower) dashed line. The upper (lower) dotted line shows 25% of the tracks falling north (south) of that line.

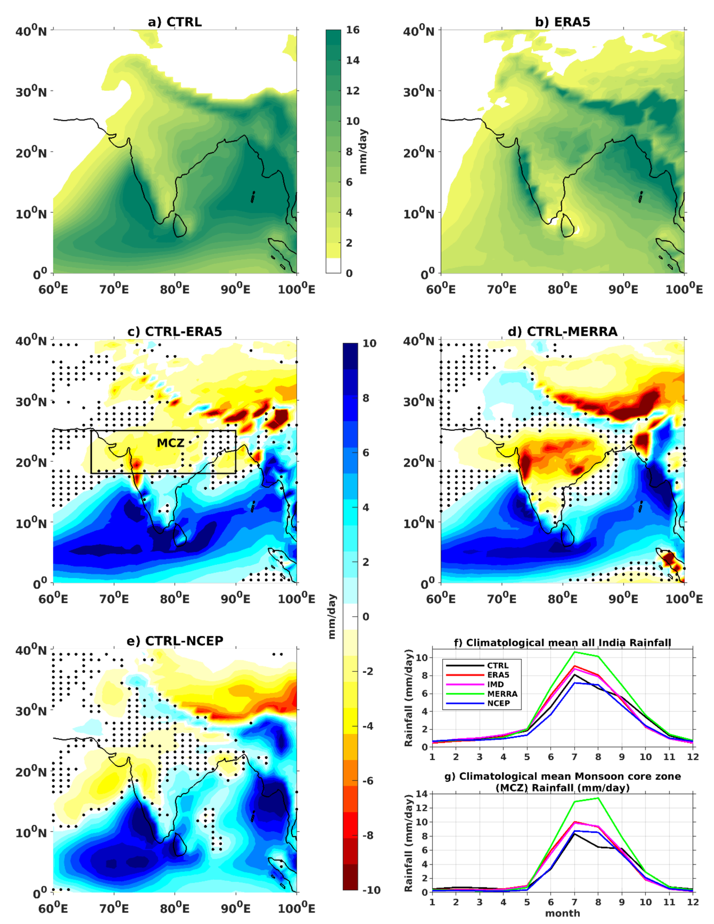

Figure-4: Climatological summer monsoon (JJAS) precipitation (in mm/day) is shown for (a) CTRL simulation, and (b) ERA5 reanalysis. Panels (c–e) show the differences in precipitation between the CTRL simulation and three different reanalysis datasets: (c) CTRL - ERA5, (d) CTRL - MERRA, and (e) CTRL – NCEP respectively. Panel (f) and (g) show the monthly climatological time series of precipitation (in mm/day) for all India, and the monsoon core zone.

- Monsoon LPS activity (Median Track, LPS track and genesis densities, precipitation, etc.) has been seen shifted towards south.

Role of horizontal wind shear and moisture:

- **Moisture & Shear**: LPSs form under cyclonic **barotropic shear** and strong **low-level moisture gradients** (Krishnamurti et al. 1975; Sikka 1977; Goswami et al. 1980; Diaz & Boos 2019a).
- **Moist Barotropic Instability**: Growth is enhanced by **moisture interacting with barotropic shear** (Diaz & Boos 2019b).
- **Moisture–Vortex Instability**: Co-amplification of **moisture and vorticity** can drive LPS intensification (Adames & Ming 2018).
- **MSE Advection: Moist static energy advection** supports both barotropic and moisture–vortex mechanisms (Luo et al. 2023).

4. Low level wind and moisture

- Monsoon low level jet is more zonal and have more cross-equatorial flow in CTRL experiment and other CMIP5 models as compared to reanalysis datasets.
- Monsoon low level jet also has been seen shifted towards south.

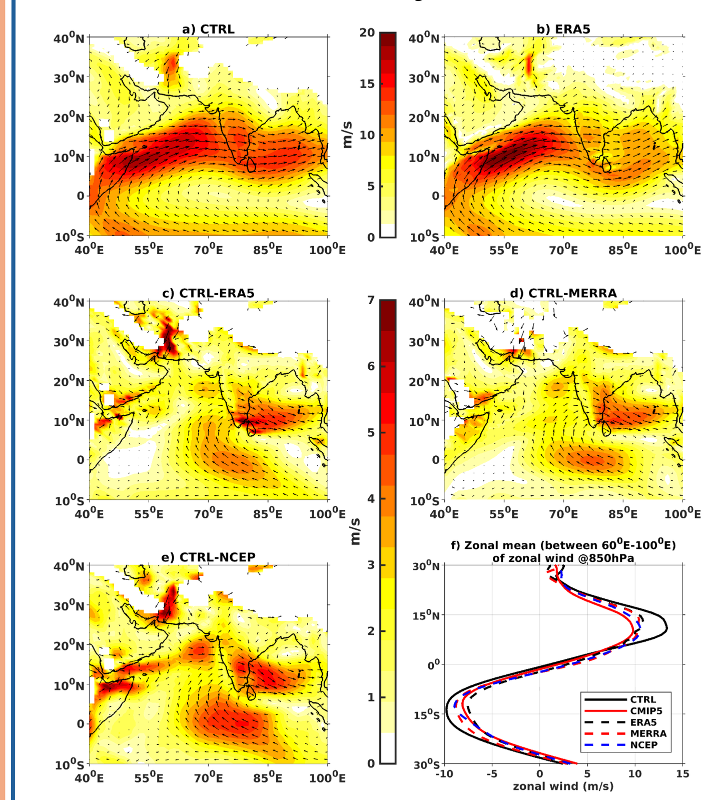

Figure-5: Climatological summer monsoon (JJAS) low level (850 hPa) winds in the (a) CTRL, and (b) ERA5 reanalysis. Panels (c–e) show the differences in the winds between the CTRL simulation and three different reanalysis datasets. Panel f shows the zonal average (over 60°E-100°E) of zonal wind at 850 hPa in the model simulation and various reanalysis datasets.

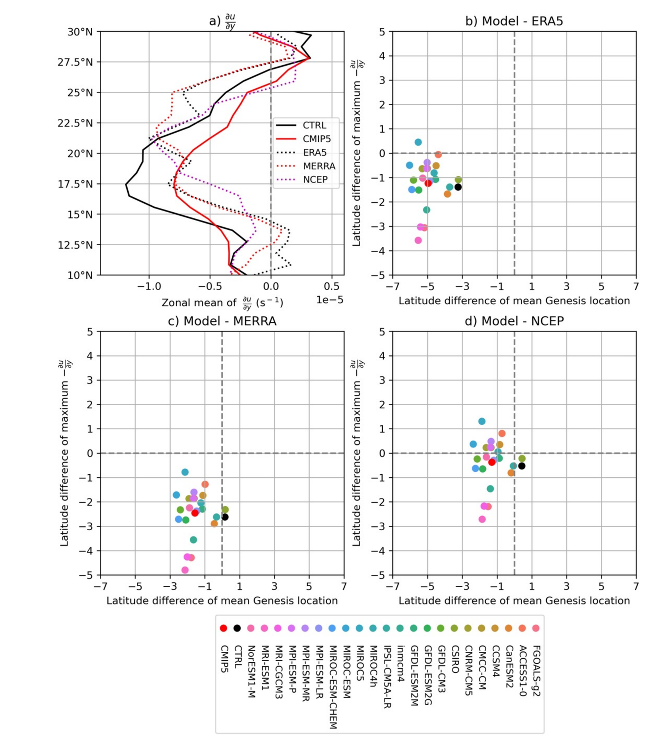

Figure-6 (a) The meridional shear of climatological 850 hPa zonal winds $\left(\frac{\partial u}{\partial y}\right)$, zonally averaged over 75°E-95°E during the Indian summer monsoon season (JJAS).. Panels (b-d) show the scatterplot between the latitude difference of the maximum meridional gradient of zonal winds $\left(-\frac{\partial u}{\partial y}\right)$ and the latitude difference of mean LPSs (or monsoon depressions) genesis locations between the models (CTRL simulation and CMIP5 models) and ERA5, MERRA, and NCEP respectively.

- CTRL shows moisture enrichment limited to south of 23°N, while ERA5 extends up to 27°N in the LPS region (70°–90°E).
- Dry bias over North and North-West India.

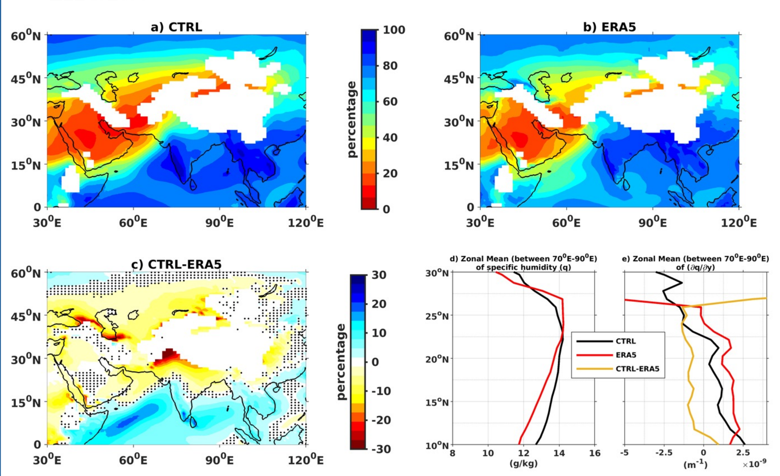

Figure 7: JJAS mean 850 hPa relative humidity for (a) CTRL and (b) ERA5; (c) shows their difference. Panels (d–e) show zonal mean specific humidity and its meridional gradient (70°E–90°E).

5. Dry air Intrusion

- The CTRL simulation and the ensemble average of all CMIP5 models show a pronounced positive subtropical high pressure bias northwest of India, relative to the reanalysis datasets.
- More dry intrusion from Northwest of North India in CTRL.

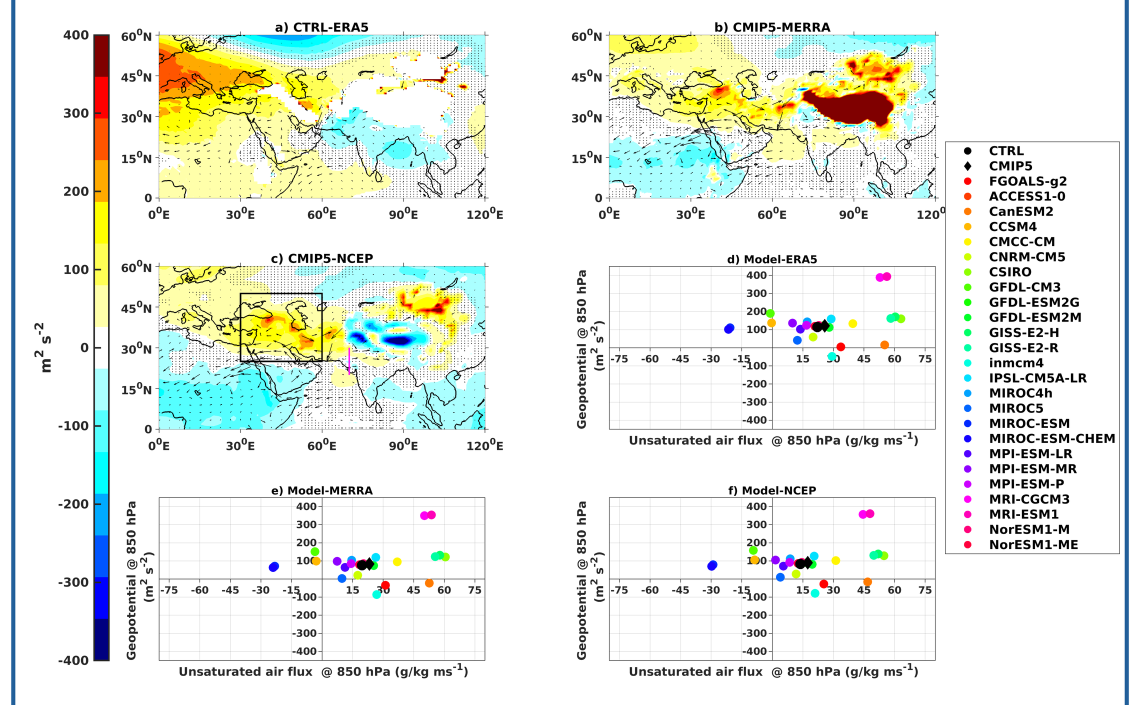

Figure 8: Panels (a–c) show JJAS climatological 850 hPa geopotential bias (shading) and vector difference in unsaturated moisture flux ($[u(q^*- q), v(q^*- q)]$; where q^* is saturated specific humidity and q is specific humidity) between CTRL/CMIP5 and ERA5, MERRA, and NCEP. Panels (d–f) show scatter plots of geopotential bias vs zonal unsaturated moisture flux (70°E, 20°–30°N) for CTRL and CMIP5 relative to the three reanalyses.

6. Conclusions

- **Wet bias over the southern peninsular India and dry bias over north India in CESM2.1.3.**
- **Southward Shift in LPS Activity**: CESM2.1.3 and CMIP models simulate a southward shift in LPS tracks, linked to a southward-displaced and more zonal monsoon low-level jet.
- **Role of Wind Shear & Moisture**: Southward bias in low-level zonal wind shear and reduced meridional moisture gradient over northern India lead to suppressed LPS activity in that region.
- **Dry Air Intrusion**: Enhanced dry air intrusion from the northwest, associated with a subtropical high-pressure bias over West Asia, contributes to dry conditions over northern India and shifts LPS genesis southward.
- **Robustness Across CMIP Phases**: Similar biases in CESM, CMIP5, and CMIP6 indicate a persistent model deficiency, highlighting the need for improved representation of monsoon dynamics and LPS processes.

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