

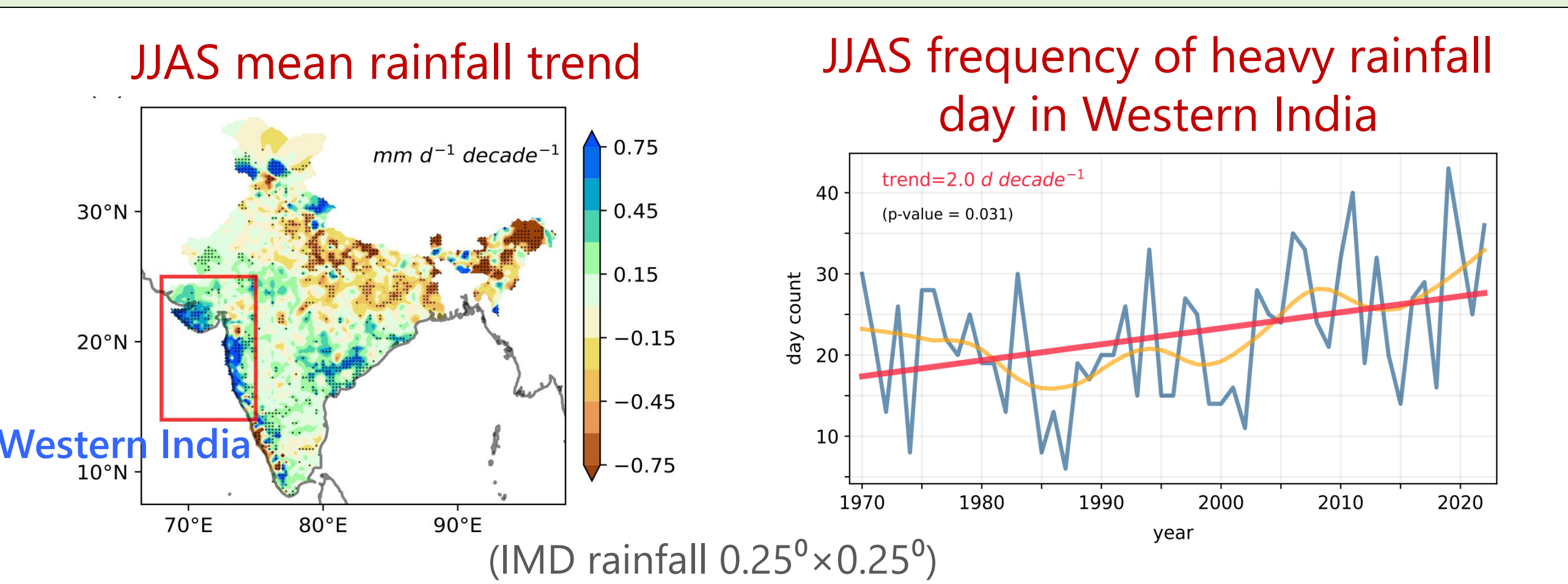
Rising monsoon extremes over western India driven by two emerging circulation regimes of contrasting spatial scales

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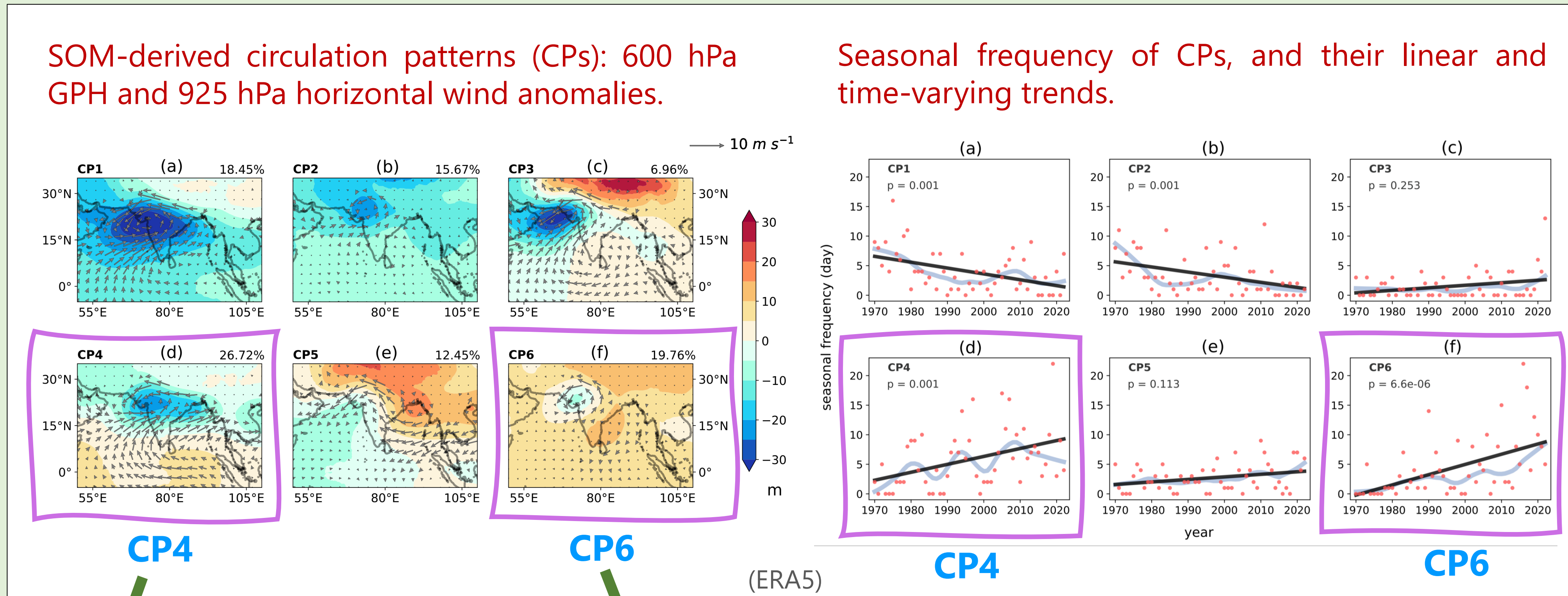
[Study period: 1970–2022]

Rainfall trend over western India

- Significantly **high wetting trends** over **western India** (red box) in monsoon season (JJAS)
- Western India — an economic and urbanization hub of India
- Heavy rainfall day: $\geq 10\%$ grids in western India receiving rainfall $\geq 95^{\text{th}}$ percentile of local climatology
- Continual rise in heavy rainfall day frequency since mid 1980s** (orange time-varying trend)

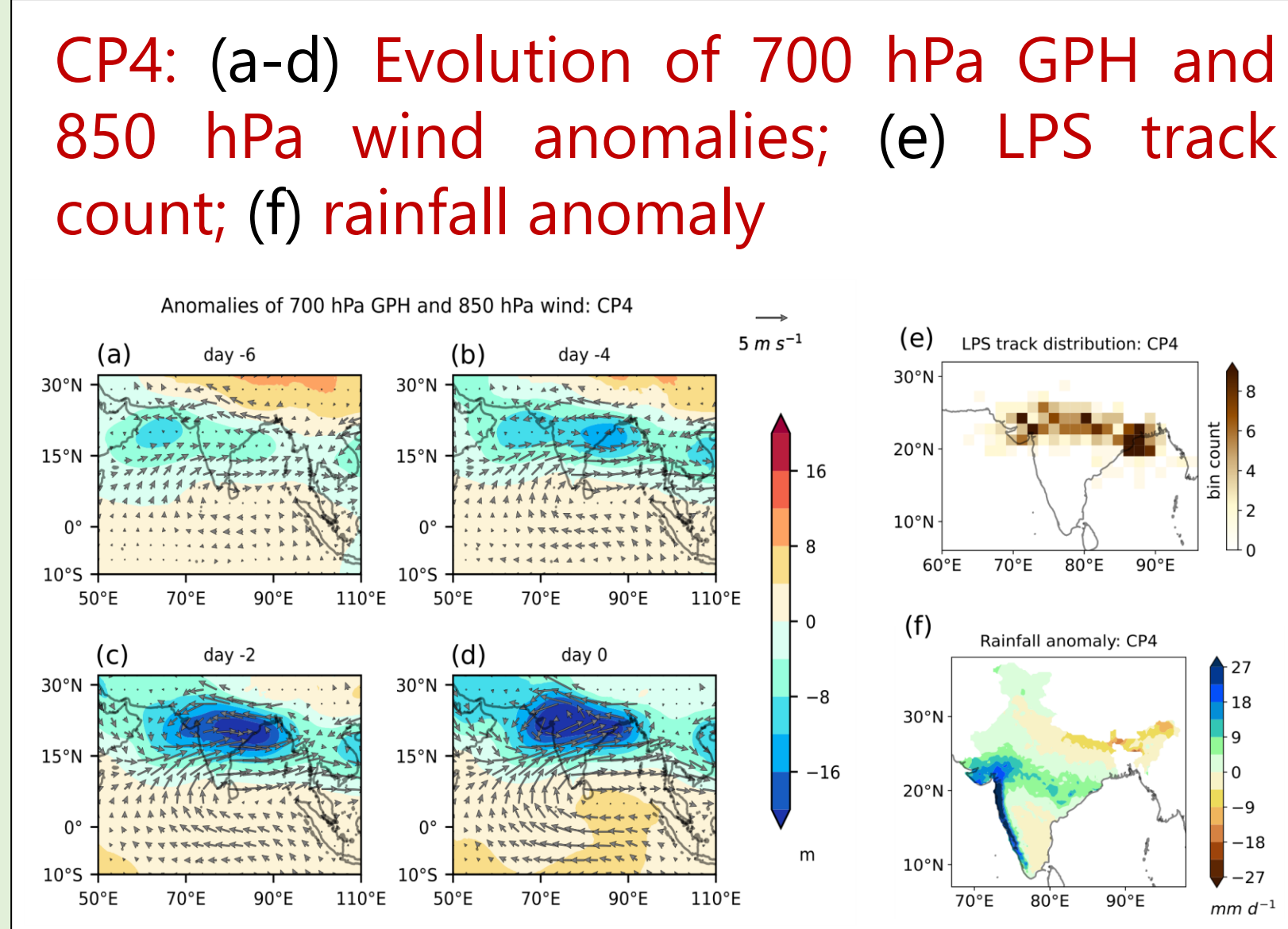
Circulation patterns (CPs): SOM clusters

- 1149 heavy rainfall days clustered into 6 CPs using **Self-organizing Map (SOM)**, an unsupervised artificial neural network that maps N-D vectors onto 2-D space
- Significant (99.9% CI) increasing trends in CP4 and CP6, consistent over time**
- CP4: Large-scale** geopotential trough and cyclonic anomalies across South Asia — strengthened monsoon southwesterlies — anomalous easterlies over Equatorial Indian Ocean (EIO)
- CP6: Localized**, weaker geopotential low and cyclonic anomalies over western India — negligible large-scale anomalies



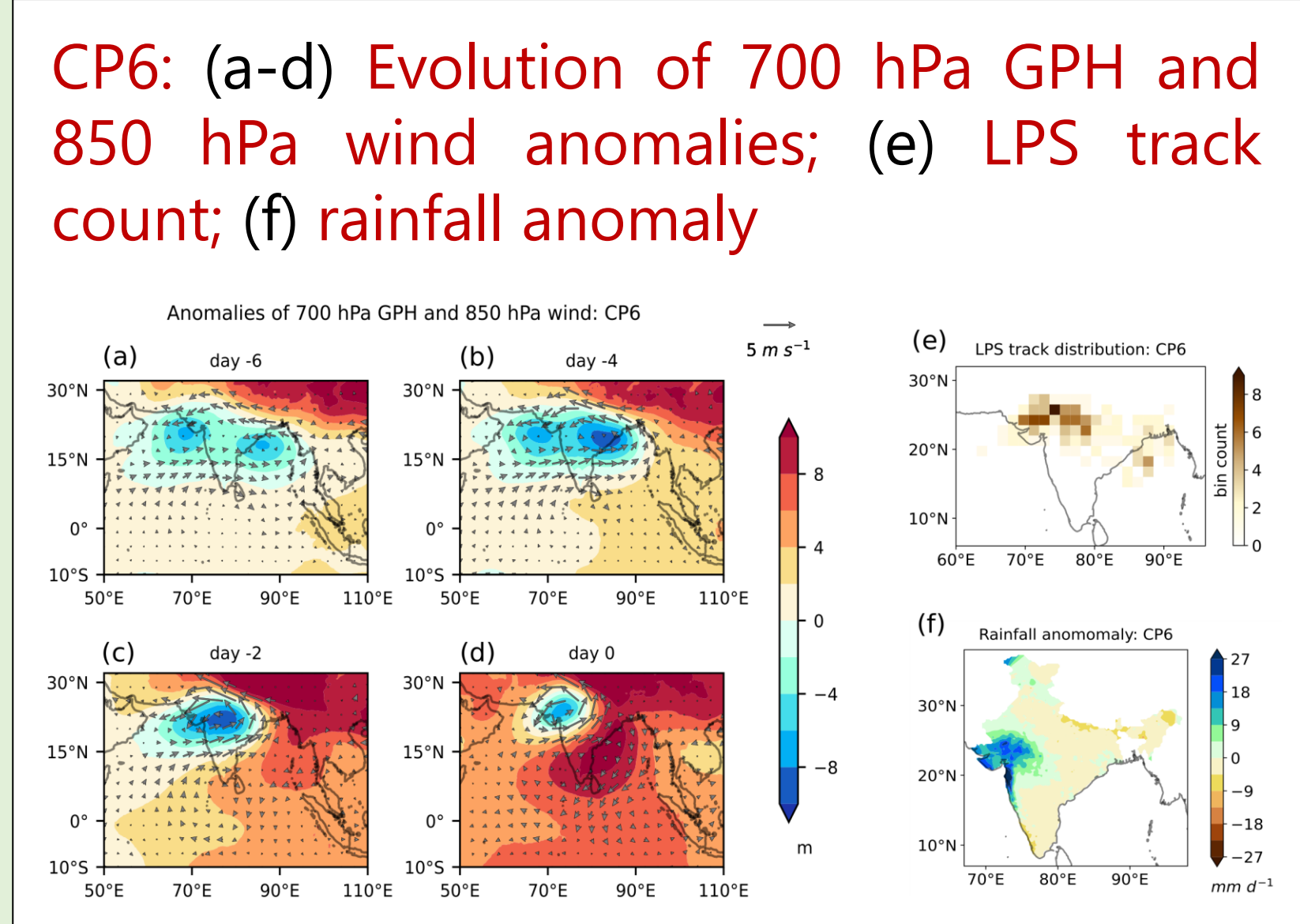
Emerging large-scale pattern: CP4

- Westward propagation of a LPS vortex across central India and merger with a pre-existing vortex over western India
- an extensive cyclonic circulation stretches across India on day 0
- Strengthened monsoon westerlies
- Widespread heavy rainfall.



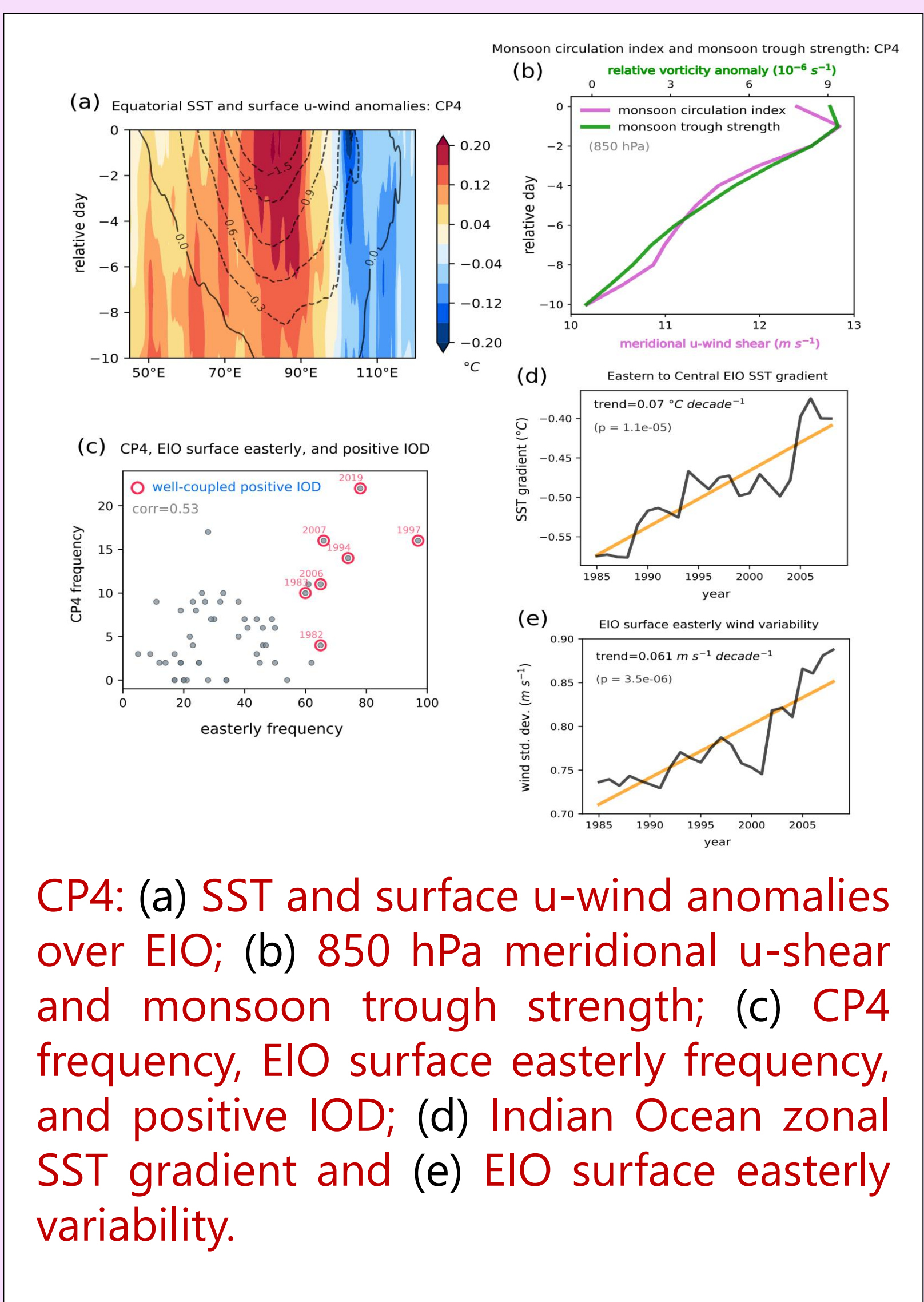
Emerging localized pattern: CP6

- Westward propagation of a LPS vortex across central India
- An isolated cyclonic circulation forms over western India on day 0
- Localized heavy rainfall.



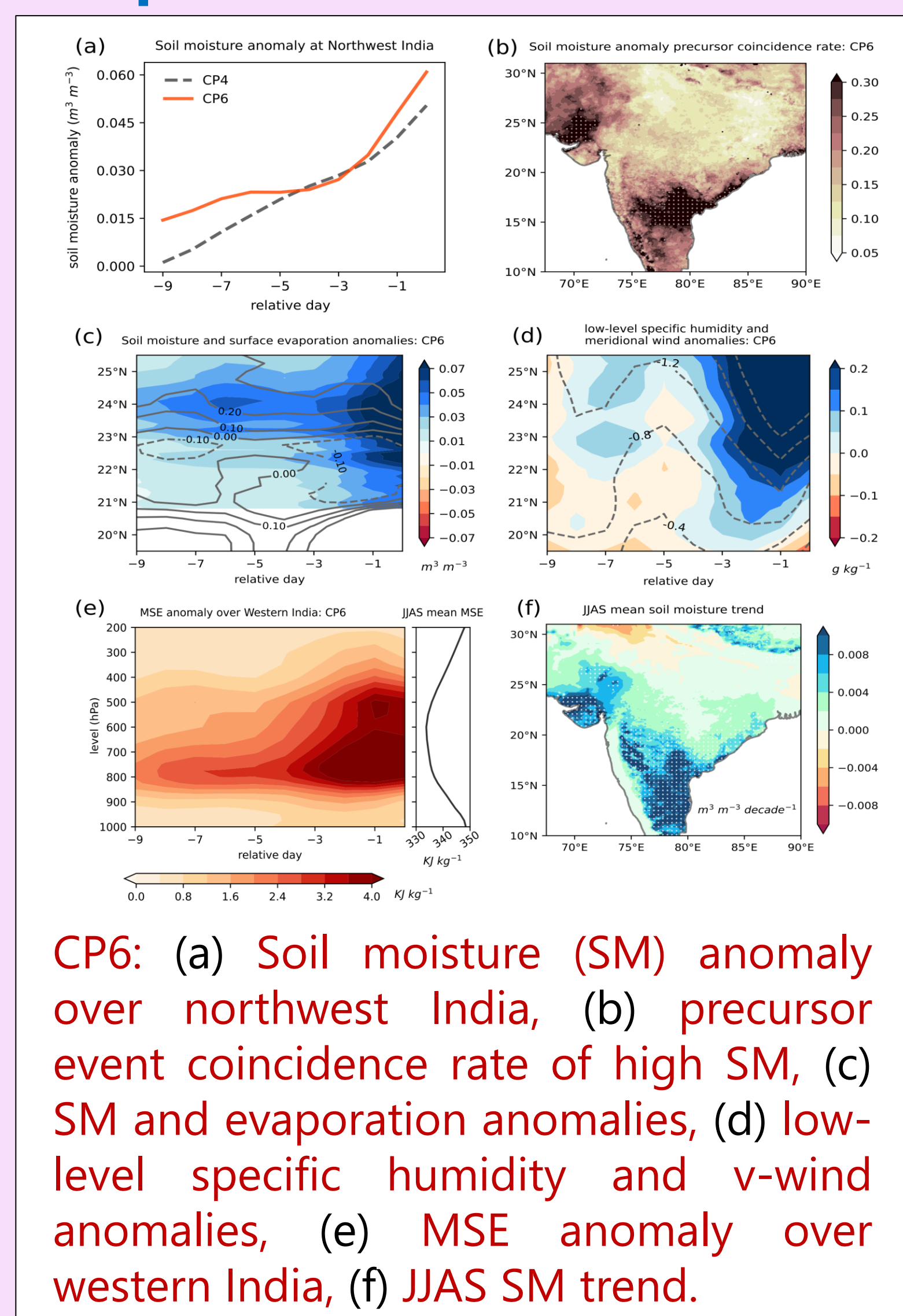
CP4 and Equatorial Indian Ocean conditions

- Strengthening of east-to-west SST gradient across EIO and associated surface easterlies
- Increasing meridional u-shear, stronger monsoon trough
- conducive for LPS development via increased barotropic instability
- Enhanced CP4 frequency** in recent decades associated with **positive Indian Ocean Dipole (IOD)**.
- Rise in CP4** $\rightarrow$ **zonally differential warming and increasing surface easterly variability over EIO**



CP6 and local land-atmosphere interaction

- Antecedent soil moisture (SM) anomaly over Northwest India ≥ 4 days before CP6
- a precursor of CP6 events
- Anomalous pre-event SM over Northwest India leads to enhanced surface evaporation
- Increased low-level moisture advected to western India by anomalous northerlies
- Increased lower free tropospheric MSE over western India intensifies LPS-related moist convection
- Rise in CP6** $\rightarrow$ **high soil wetting trend over northwest India**



Takeaway

Persistent rise in extreme rainfall over western India is driven by two emerging weather patterns

The large-scale pattern
 $\downarrow$
Remote ocean-atmosphere conditions at EIO

The localized pattern
 $\downarrow$
Local land-atmosphere interaction

Improving the realism of convection-circulation coupling, surface fluxes and land-atmosphere interactions, and transient ocean-atmosphere processes in climate models is essential for credible simulation of extreme monsoon rainfall.

Check out the publication

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