

# Case studies of the Monsoon Onset Vortex and early season Monsoon features using the UFS coupled model

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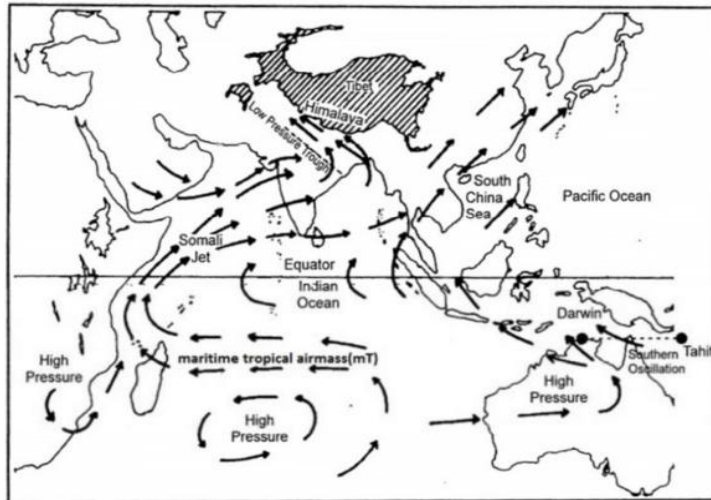


The background is a solid orange color. In the top-left corner, there are three vertical bars of varying heights, each composed of several overlapping semi-transparent orange circles. In the bottom-right corner, there are four vertical bars of increasing height from left to right, also composed of overlapping semi-transparent orange circles.

# Background and Introduction

# An overview of the Indian Summer Monsoon

- Extends from June to September
- Mascarene High
- Somali Jet (low level jet at 850 hPa)



- Tropical easterly jet (TEJ)
- Tibetan High

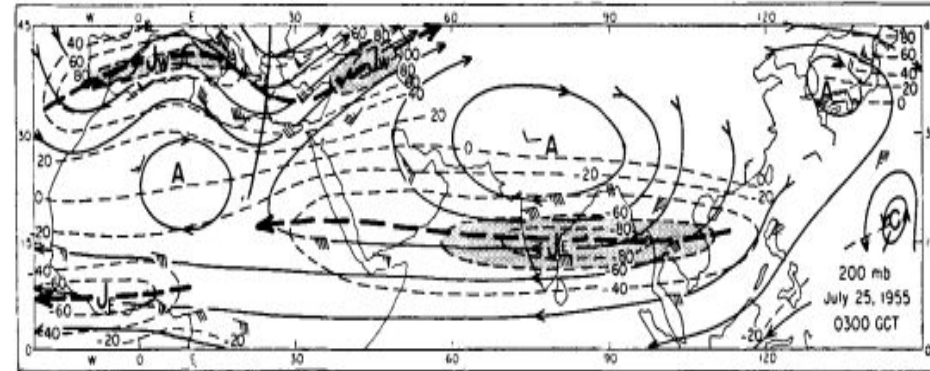
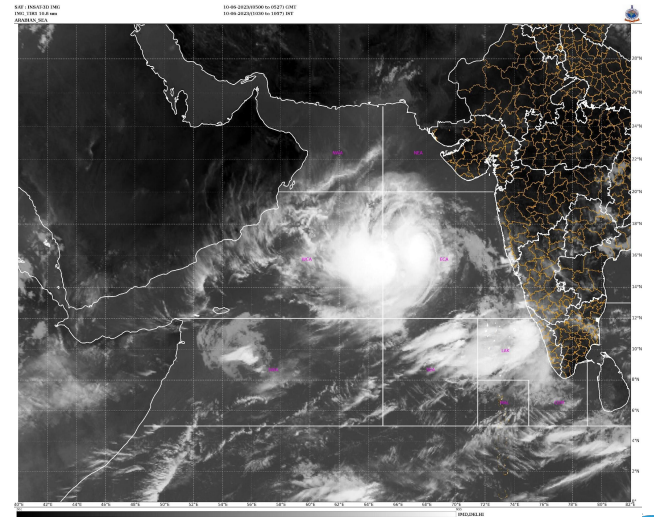


Fig. 4 c. Streamlines and isotachs 200 mbs, July 25, 1955. Jet axis marked heavy and wind maxima shaded. Image from Koteswaram, P. (1958)

# The Monsoon Onset Vortex (MOV)

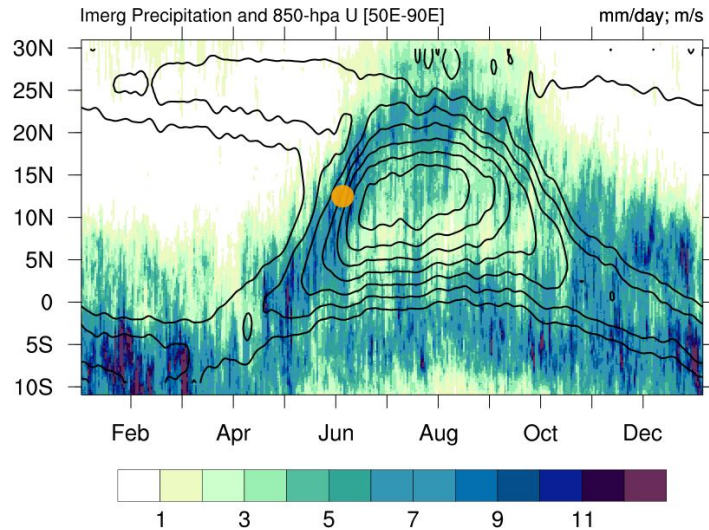
- During the Monsoon, there is high vertical wind shear over the Arabian Sea: low-level westerlies and upper-level easterlies
- Tropical cyclogenesis is rare during the core monsoon period of July-August
- However, during the Monsoon onset phase (late May-early June), a vortex forms in the Arabian Sea in ~60% of the years
- This vortex is termed as the Monsoon Onset Vortex (MOV) - **synoptic scale feature, part of the planetary scale monsoon circulation**
- Recent example: Cyclone Biparjoy in the Arabian Sea, June 2023

Cyclone Biparjoy - Infrared image from INSAT 3D during June 10, 2023



(Image credits: India Meteorological Department)

# MOV in the context of the northward shift of monsoon precipitation



MOV formation coincides with the rapid increase of zonal wind and the seasonal northward shift of precipitation.

Figure: Latitude-time Hovmöller of climatological rainfall rate (shaded; mm day<sup>-1</sup>; NASA IMERG) and zonal wind (contours; ms<sup>-1</sup>; ERA-interim) averaged over 50E-80E longitudes. The median MOV genesis location (1980-2021) is marked by the orange dot.

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# Why study the MOV

## 1. Affects the advance of the Monsoon

- Helps set in the Monsoon over southern India (e.g., Krishnamurti et al., 1981)
- The MOV track/intensity can possibly delay the monsoon progression over the west coast of India and in the interior peninsula

## 2. Considerable Socio-Economic impacts

- MOVs often intensify into TCs (~78%), coastal hazards for densely populated coastline
- Past MOVs have caused damages worth \$4 billion (Evan and Camargo, 2011)
- Agricultural and hydrological impacts through modulation of subseasonal monsoon rainfall

**No previous studies have focused on the predictability of the MOV and associated impacts on the early-season monsoon forecasts in short-medium range forecasts of global models.**

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# Research Questions

1. Past studies have indicated the strength of the Somali Jet index to be related to the monsoon rainfall over India. Does the UFS capture this relationship correctly, specifically for the earlier part of the monsoon season?
2. How well does the UFS forecast the MOV at a lead time of <10 days (case studies of the MOVs in 2011, 2014 and 2015)
  - a. What dynamical/thermodynamical factors are likely to affect the MOV forecasts?
3. How do MOV forecasts impact the early-season monsoon rainfall over the Indian region?

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# Data

- **UFS S2S prototypes – P5, P6 and P8**

## Validation Data:

- Atmosphere – ERA5 reanalysis
- MOV tracks – Joint Typhoon Warning Center (JTWC) Best track data
- Rainfall – GPM IMERG

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# Large-scale features of the Monsoon

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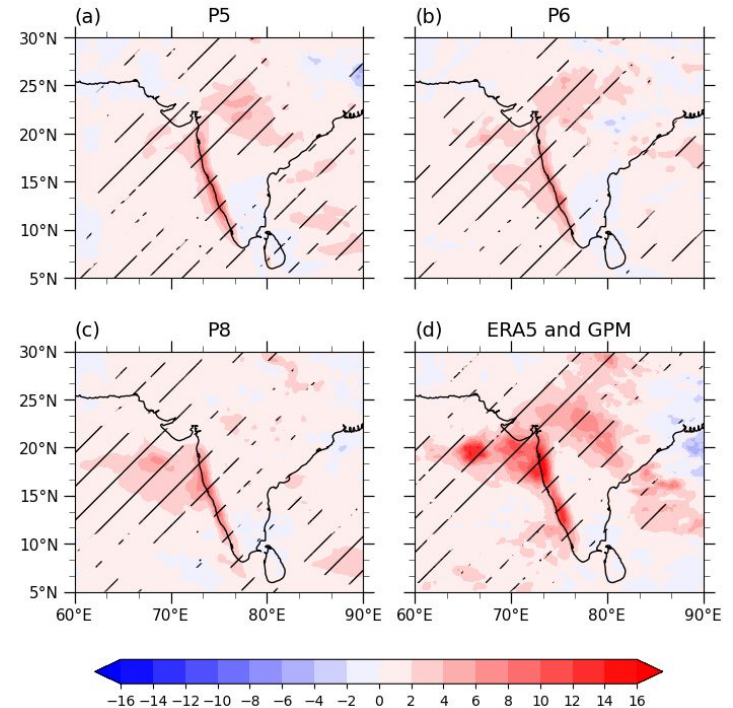
# Somali Jet Index and Monsoon Rainfall

- Somali Jet Index – defined by Boos and Emanuel (2009).
- Given by the square root of twice the spatial mean kinetic energy of 850 hPa horizontal wind over the Arabian Sea (5°S-20°N, 50°E-70°E).
- **Strong 850 hPa winds over the Arabian Sea are linked with above normal rainfall over the west coast and central parts of India (Rajeevan et al., 2010)**
- **MOV formation linked with the Somali Jet – cyclonic vorticity north of the jet, barotropic instability (Krishnamurti et al., 1981)**
- How well do the UFS S2S prototypes capture this feature for the early-season period?

# Somali Jet Index and early-season Monsoon Rainfall

- Time period: June 15 – July 19 during 2011-2017
- Areas marked by black lines are statistically significant at 95% confidence level.
- Spatial pattern of the anomalous increase in rainfall – captured well in P5.
- Anomalous rainfall off the west coast of India captured well in P8.
- **All prototypes underestimate the rainfall amount**
- **Implies lesser rainfall predicted by the UFS for the west coast and central parts of India for active phases of the monsoon.**

Anomalous rainfall (mm/day) for 1 std. dev of jet index

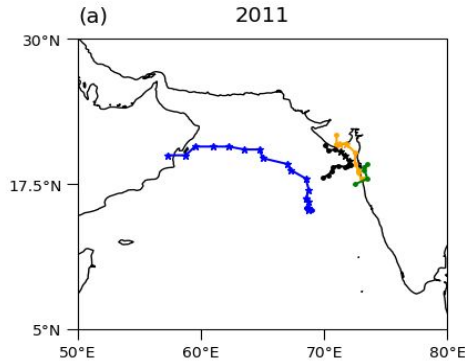


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# MOV Cases

# MOV formations and tracks

MOV tracks



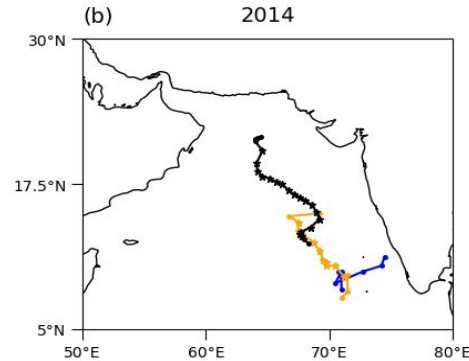
## 2011 MOV

Formed on 06 UTC on June 9, becomes a TC.

**P5:** Forms on ~18 UTC on June 3, becomes a TC, westward track.

**P6:** Forms ~ 00UTC of June 5, becomes a TC.

**P8:** Forms by ~00 UTC of June 4, no TC.



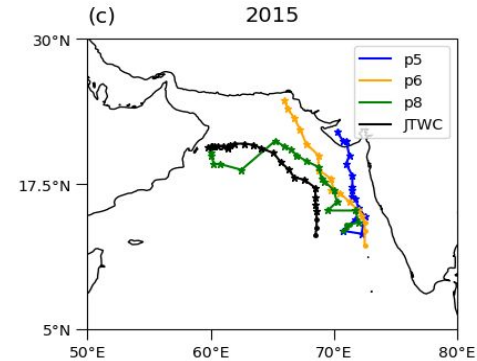
## 2014 MOV

Formed on 06 UTC on June 8, becomes a TC.

**P5:** Forms same day, weaker, no TC, east-northeastward track.

**P6:** Forms ~ 18UTC of June 6, becomes a TC.

**P8:** No MOV forms in the UFS.



## 2015 MOV

Formed on 06 UTC on June 6, becomes a TC.

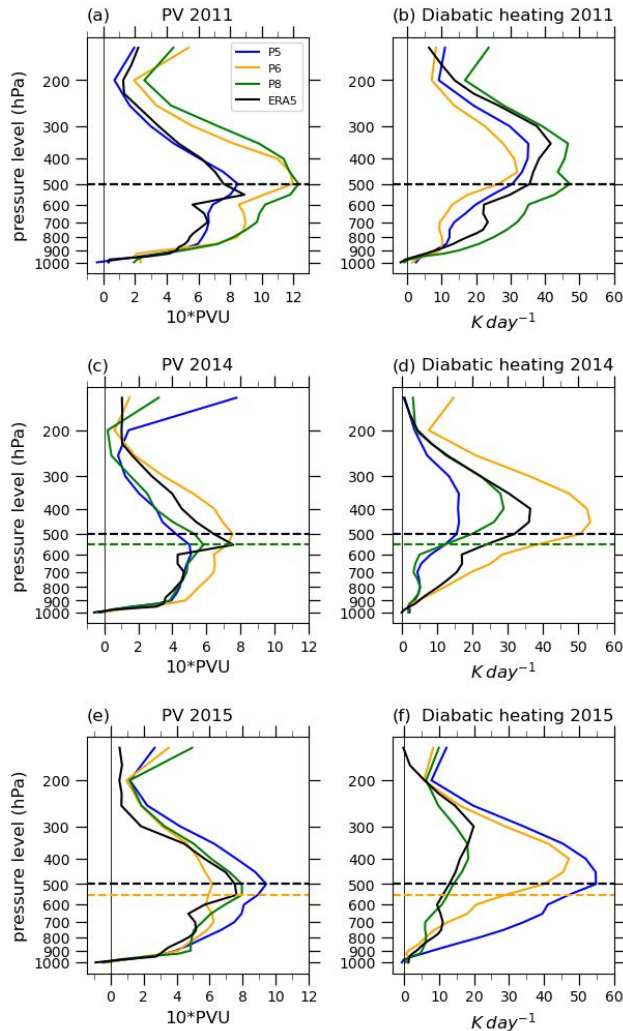
**P5:** Forms same day ~00UTC, more northward track.

**P6:** Forms same day ~ 00UTC of June 6.

**P8:** Forms same day/time. Track and intensity closest to observations.

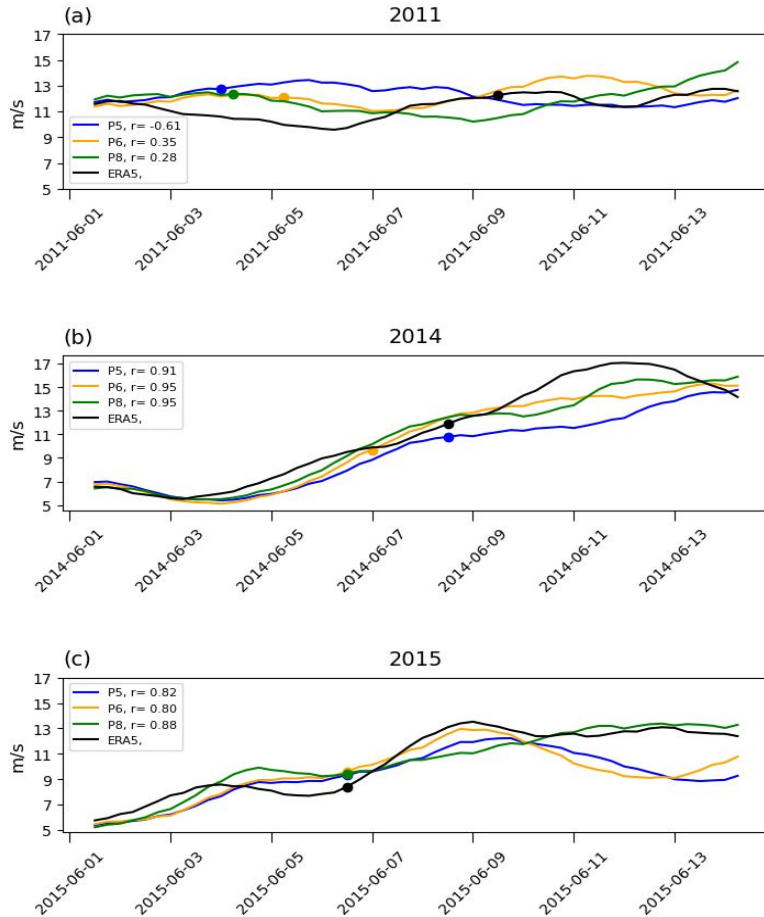
# Possible thermodynamical factors influencing MOV forecasts

- Diabatic heating is the main contributor to the MOV's Potential Vorticity (2 maxima in PV) structure and growth in its formation stage (Dhavale et al., 2025)
- PV and diabatic heating profiles of UFS match the closest to ERA5 for 2015 MOV in P8 – was the best forecasted case



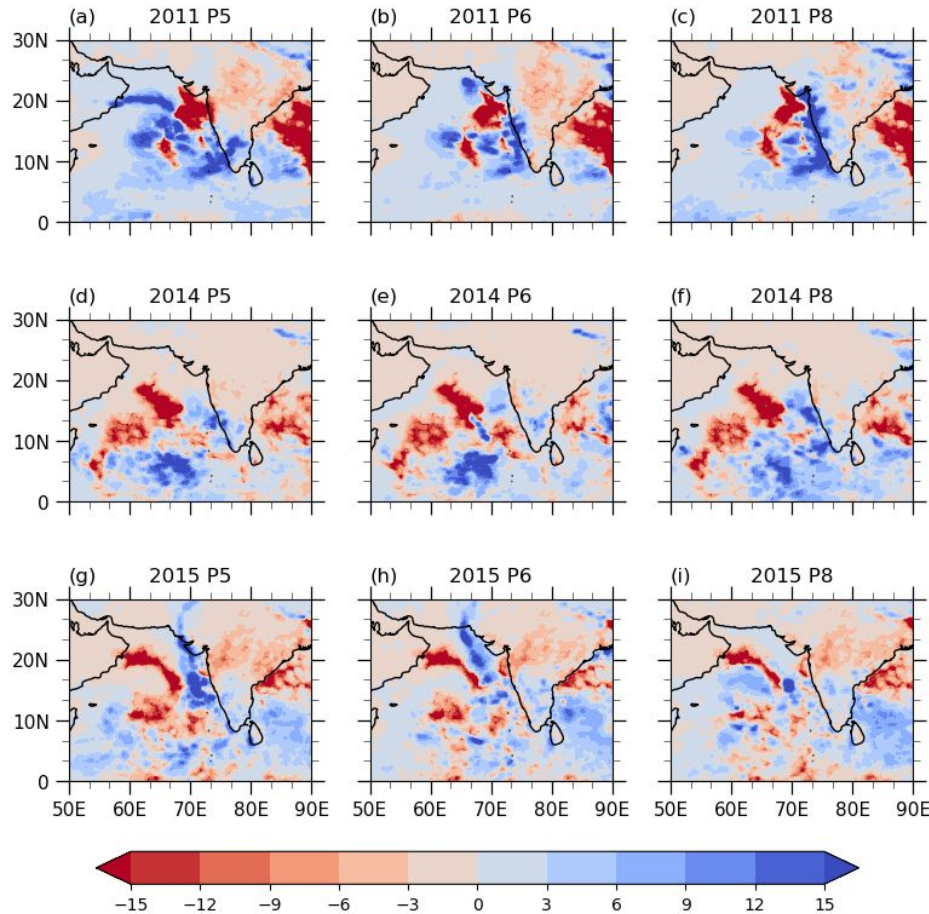
# Somali Jet Index

## Somali Jet Index



- A measure of the dominant wind feature over the Arabian Sea
- Not well predicted in 2011 from the beginning – initial conditions?
- Well predicted in 2014, high correlation. But still, no MOV forms in P8
- Well predicted in 2015, high correlation. Magnitude matches well in P8 even after MOV formation
  - Accurate MOV forecast, accurate background winds even after the MOV
- Accurate forecast of the Somali Jet index is necessary, but not sufficient?

Precipitation difference ( $mm\ day^{-1}$ ) June 1-14



# Impact of MOV forecasts on subseasonal rainfall – focus on west coast of India

- The west coast of India is a very heavy rainfall region (~15-25 inches in June)
- Rainfall is highest along the MOV track
- Large precipitation differences attributed to MOV forecasts – highest for 2011 MOV
- Good MOV forecasts □ less rainfall difference over land (P6 in 2014, P8 in 2015)



# Summary

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# Key Takeaways

- Somali Jet index and monsoon rainfall relation captured reasonably well in the UFS – underestimates the anomalous increase in rainfall for a stronger jet
- **2015 MOV is the best forecasted** – P8 has the correct intensity, track, Somali Jet index, and rainfall forecasts
- **2011 MOV is not well forecasted** – possible role of initial conditions?
- **Predicting both the evolution of convective features on a mesoscale to synoptic scale and the background wind conditions is essential for accurate MOV forecast**
- MOV is an extreme weather event forming during the monsoon onset phase
  - MOV forecasts have implications for early-season monsoon rainfall - can affect the skill of subseasonal forecasts
- 850 hPa zonal wind and OLR are important parameters for the calculation of BSISO index – may affect the monsoon forecasts at a shorter time scale (**monsoon intraseasonal oscillations**)
- Future work: More cases, ensemble runs, additional metrics for evaluation

*Manuscript submitted to Weather and Forecasting (under review)*

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# Acknowledgements

- NOAA WPO and UCAR CPAESS for the WINGS Fellowship
- PhD advisor Dr. Anantha Aiyyer at North Carolina State University, WINGS mentor Dr. Cristiana Stan (George Mason University)
- My PhD advisory committee (Dr. Gary Lackmann, Dr. Walter Robinson, and Dr. Sarah Larson) at North Carolina State University
- Dr. Cindy Bruyère (and Kate Rodd) from CPAESS for their constant support.

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# References

1. Boos, W. R., & Emanuel, K. A. (2009). Annual intensification of the Somali jet in a quasi-equilibrium framework: Observational composites. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 135(639), 319-335.
2. Dhavale, S., and Aiyyer, A. (2025). The Structure of a Developing Arabian Sea Monsoon Onset Vortex: Role of Moist Convection. *Journal of Atmospheric Sciences* (under review).
3. Evan AT, Camargo SJ. 2011. A climatology of Arabian Sea cyclonic storms. *Journal of Climate*, 24(1): 140–158. <https://doi.org/10.1175/2010JCLI3611.1>.
4. Krishnamurti, T. N., P. Ardanuy, Y. Ramanathan, and R. Pasch, 1981: On the Onset Vortex of the Summer Monsoon. *Monthly Weather Review*, 109 (2), 344.
5. Koteswaram, P. (1958). The easterly jet stream in the tropics. *Tellus*, 10(1), 43-57.
6. Rajeevan, M., Gadgil, S., & Bhate, J. (2010). Active and break spells of the Indian summer monsoon. *Journal of earth system science*, 119, 229-247.

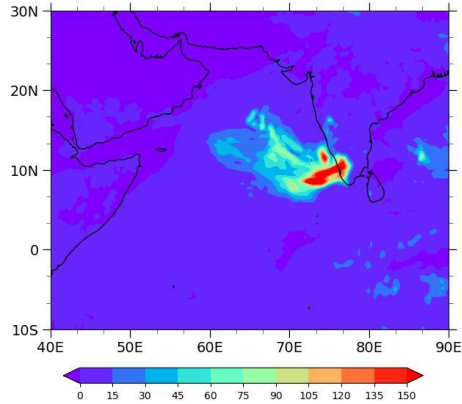


# Supplementary slides

# 2011 MOV

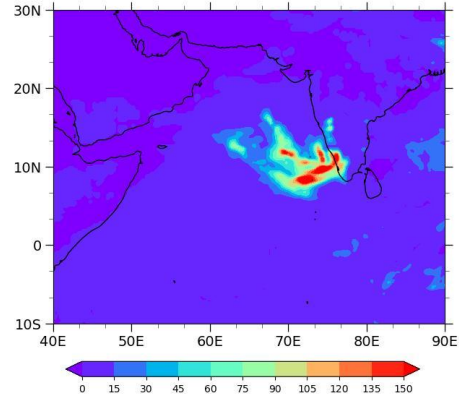
Total Precipitation: Initialized 2011-06-01T00 UTC, valid for 2011-06-01

P5



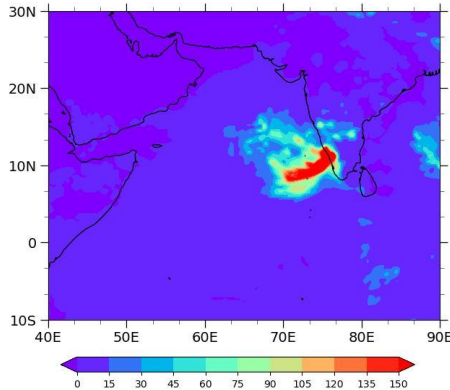
Total Precipitation: Initialized 2011-06-01T00 UTC, valid for 2011-06-01

P6



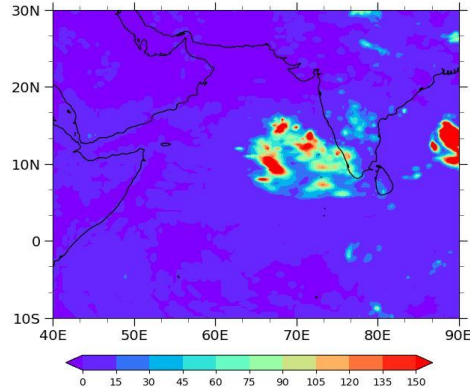
Total Precipitation: Initialized 2011-06-01T00 UTC, valid for 2011-06-01

P8



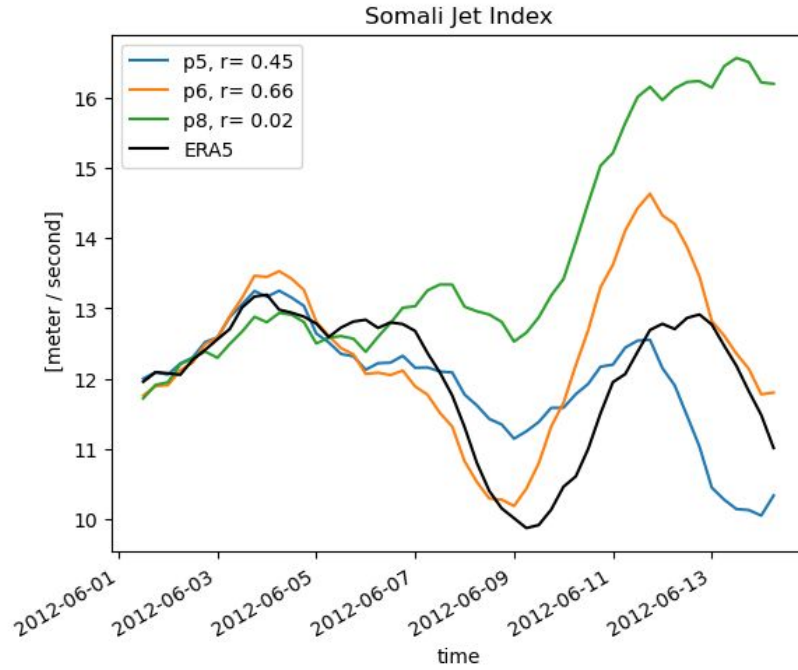
Daily Precipitation from GPM 20110601

GPM



Some “UFS feature” causing the rainfall spatial pattern to remain very similar across the prototypes.

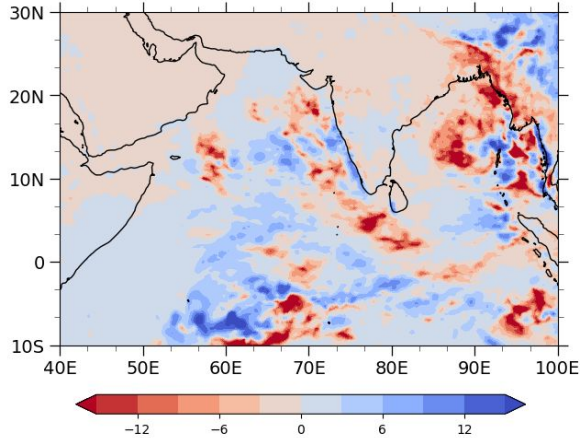
# Somali Jet index in 2012: non-MOV year



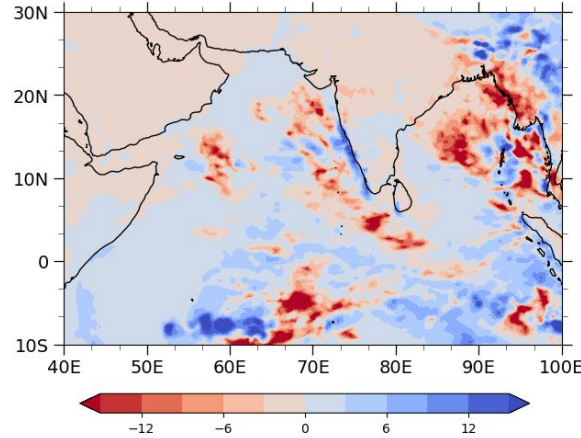
- Somali Jet index in UFS matches well in ERA5 in magnitude till June 5, but the correlation is the highest in P6.
- Not forecasted well in the UFS beyond June 7.

# Rainfall difference from June 1-14, 2012

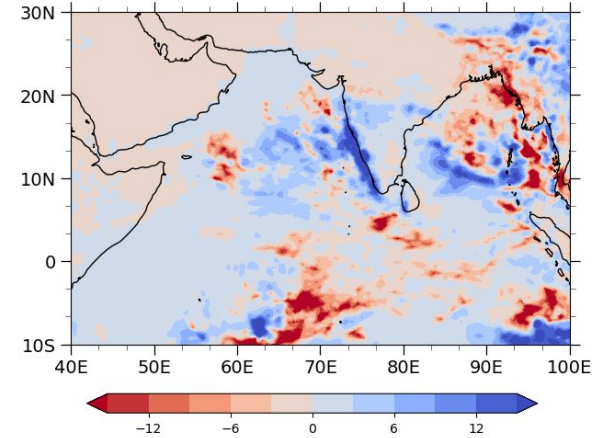
Precipitation difference ( $mm\ day^{-1}$ ) in P5 from June 1-14, 2012



Precipitation difference ( $mm\ day^{-1}$ ) in P6 from June 1-14, 2012



Precipitation difference ( $mm\ day^{-1}$ ) in P8 from June 1-14, 2012



- Higher rainfall over the west coast of India in P8 – Somali jet index is also the highest in P8.
- The least rainfall bias for the coastal regions of India is in P5.