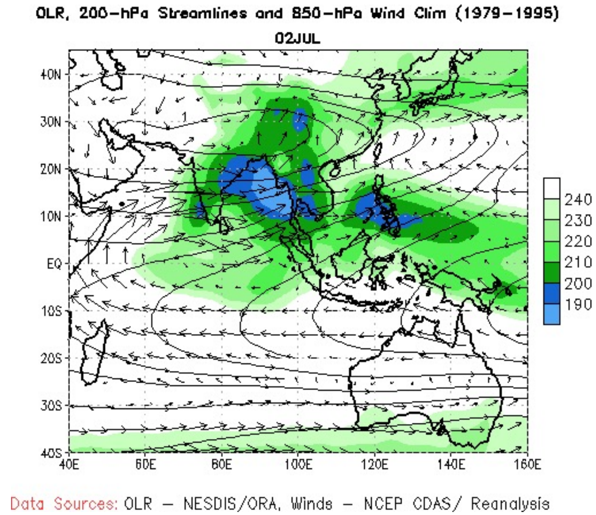
Indian Monsoon Precipitation and Circulation Teleconnections with Tropical Indian Ocean heating in the Community Earth System Model (CESM)



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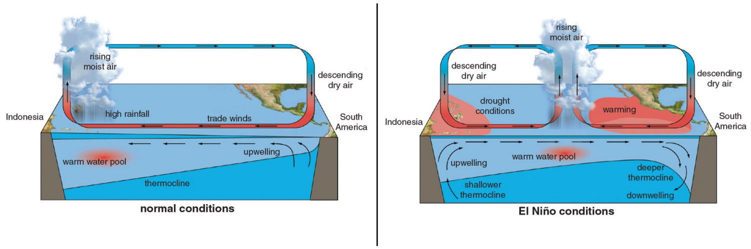
OUTLINE

- What is Teleconnections?
- Monsoon
- What is ENSO IOD EQUINOO and their link with monsoon
- Motivation and Research Questions
- Observational Results
- Model experiments
- Key findings
- Limitation and Future Scope

What is Teleconnections?

ENSO



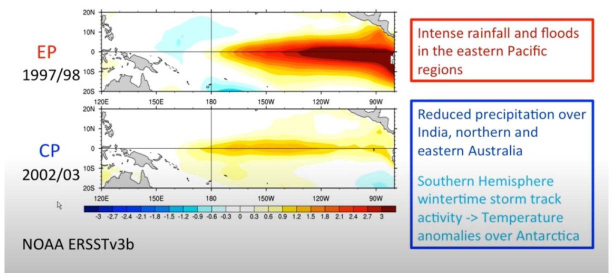
El-Nino Conditions:

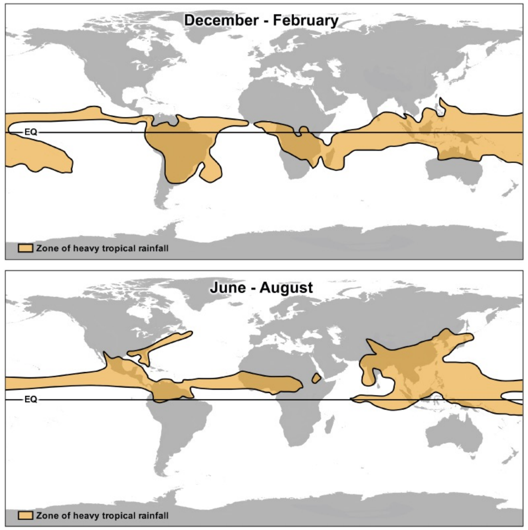
- Weaker easterly winds result in less upwelling of cold water
- Warm SSTs “spread” to east Pacific (also solar heating not offset by upwelling)
- Increase in the east Pacific thermocline
- Low pressure and convection shifts to the east Pacific
- High pressure and subsidence shifts to the west Pacific

Normal Conditions or La Nina:

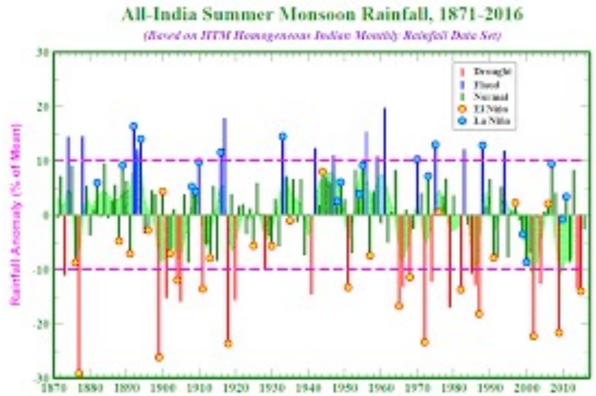
- Strong easterly winds induce upwelling of cold water in the equatorial eastern Pacific
- Shallow oceanic thermocline in the east Pacific (due to upwelling)
- Warm SSTs confined to western Pacific with a deep thermocline
- Low pressure and convection in west Pacific
- High pressure and subsidence (clear air) in east Pacific

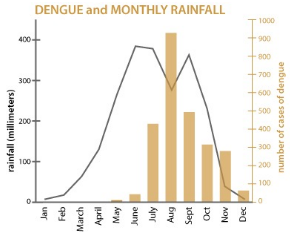
ENSO diversity has been primarily identified with different SST patterns characterized by SST maximum at different longitudes

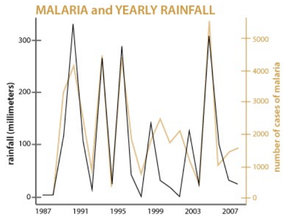




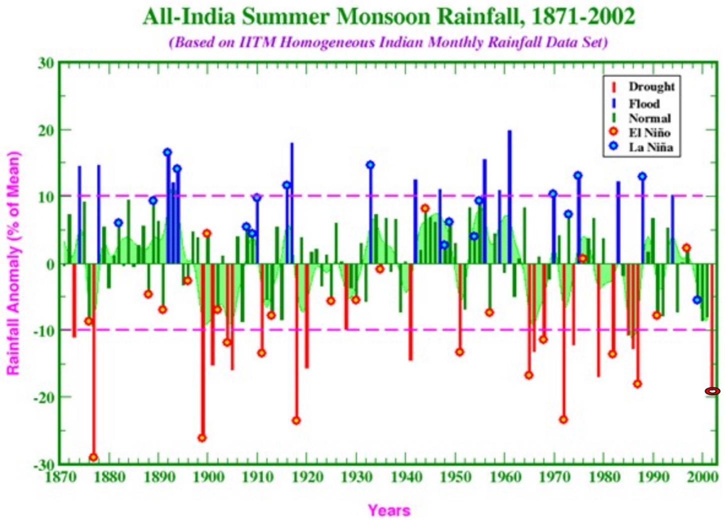
MONSOON

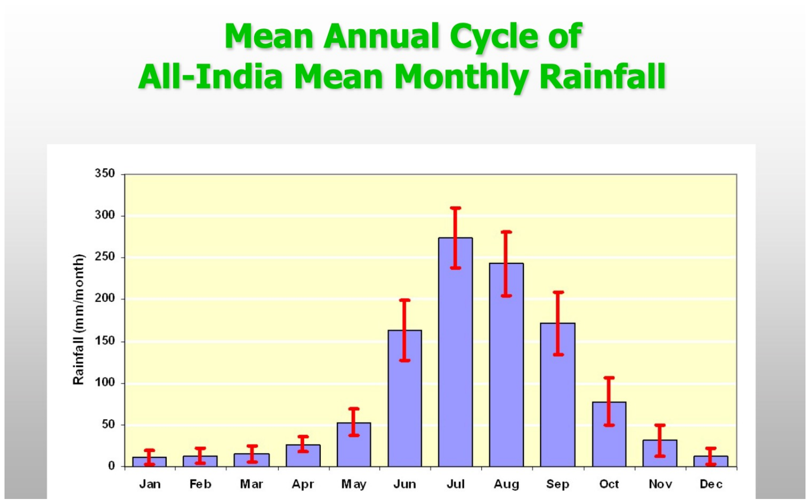




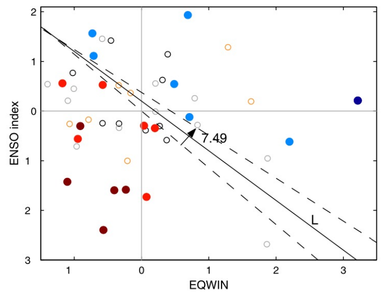


A changing monsoon affects every form of life that depends on it.



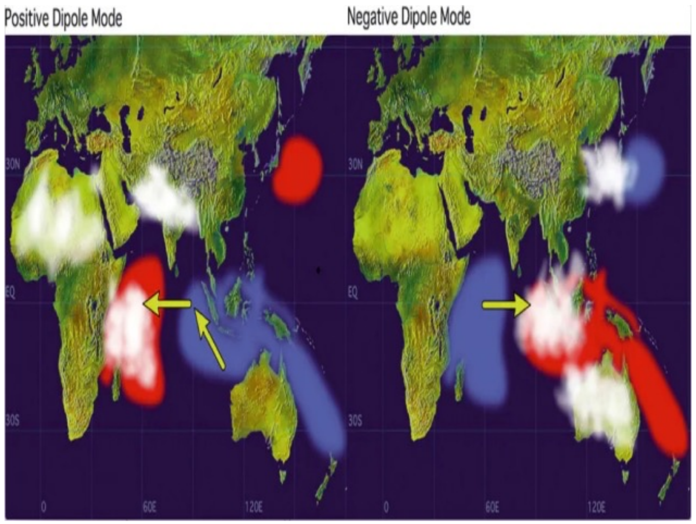


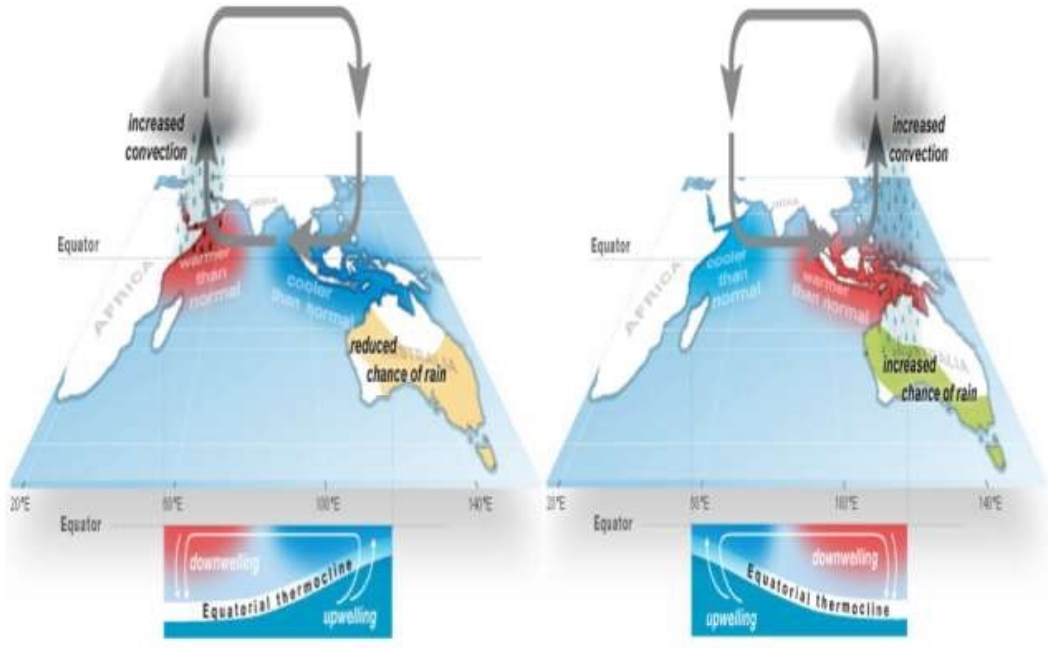
The **EQWIN** is the negative of the (normalized) anomaly of the zonal component of the surface wind at the equator (60°E – 90°E, 2.5°S – 2.5°N). EQWIN is highly correlated (coefficient 0.81) with the difference between OLR of WEIO and EEIO.



Each season during 1958–2003 is shown on the phase plane of the June to September average of the **ENSO index** (negative of Nino 3.4 index) and EQWIN. The corresponding ISMR anomaly (normalized by the standard deviation) is represented with different symbols: large dark blue (red) closed circles for values above (below) 1.5 (- 1.5), blue (red) closed circles for values between 1 (-1) and 1.5 (-1.5), small black (orange) open circles for values between 0.25 (- 0.25) and 1 (- 1) and small gray open circles for values between - 0.25 and 0.25.
(From Gadgil et al. 2004)

Indian Ocean Dipole (IOD)



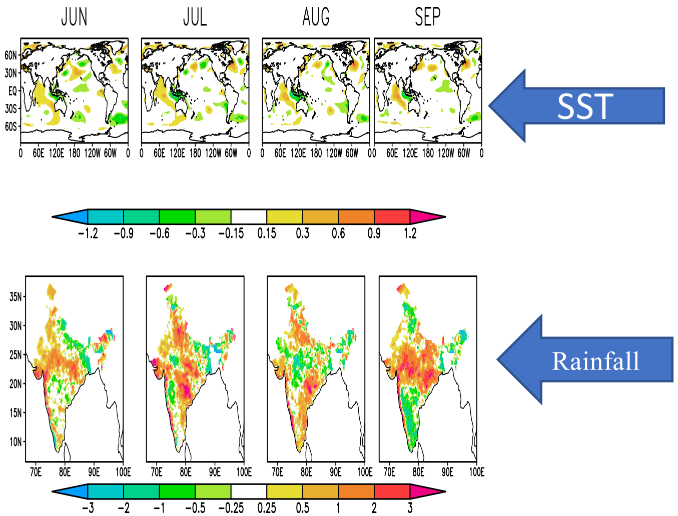


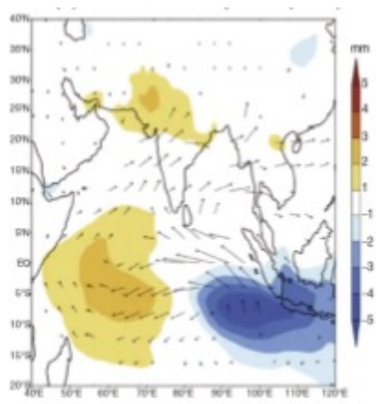
Indian Ocean Dipole (IOD): **Positive phase**

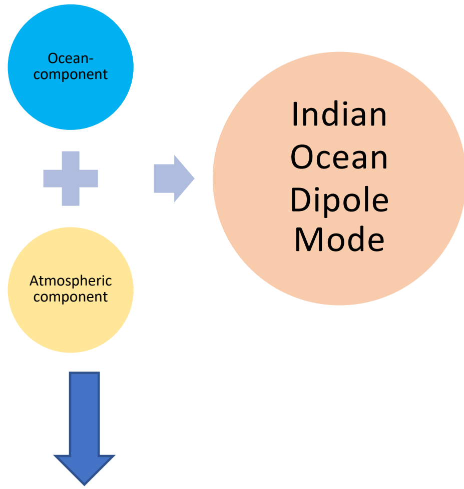
Indian Ocean Dipole (IOD): **Negative phase**

- About 20% of the IOD events seem to co-occur with ENSO
- Climate modeling experiments confirm that IOD events are often triggered by ENSO, but they also demonstrate that IOD events can exist without ENSO by means of dedicated sensitivity experiments in which ENSO is removed by different nudging techniques (Lau and Nath, 2004; Fischer et al., 2005; Behera et al., 2006; Wang et al., 2016; 2019; Cretat et al., 2017, 2018).

Large +ve IOD without Strong El Nino



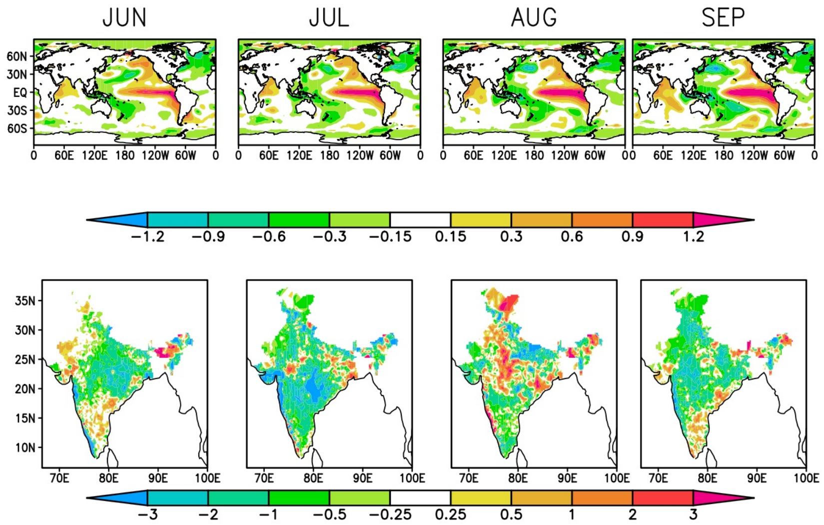




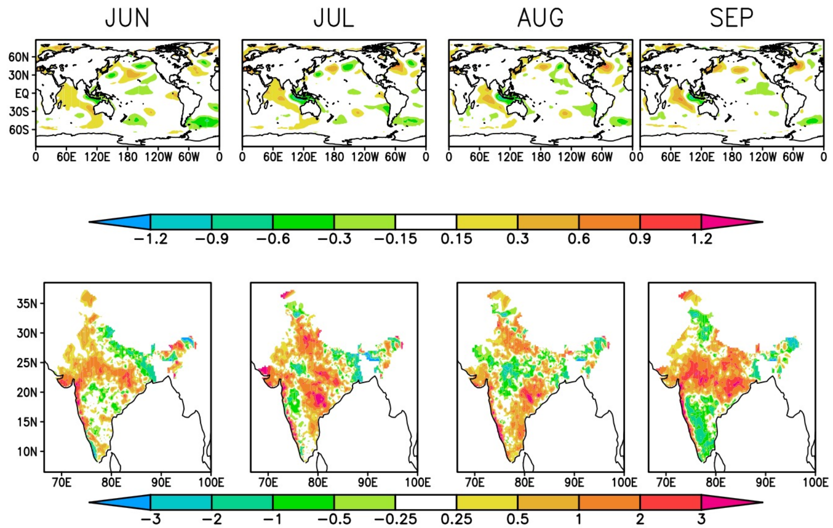
DMI is not as well correlated with rainfall as EQUINOO.

(Saji et al., 1999; Webster et al., 1999) (Graham and Barnett, 1987)

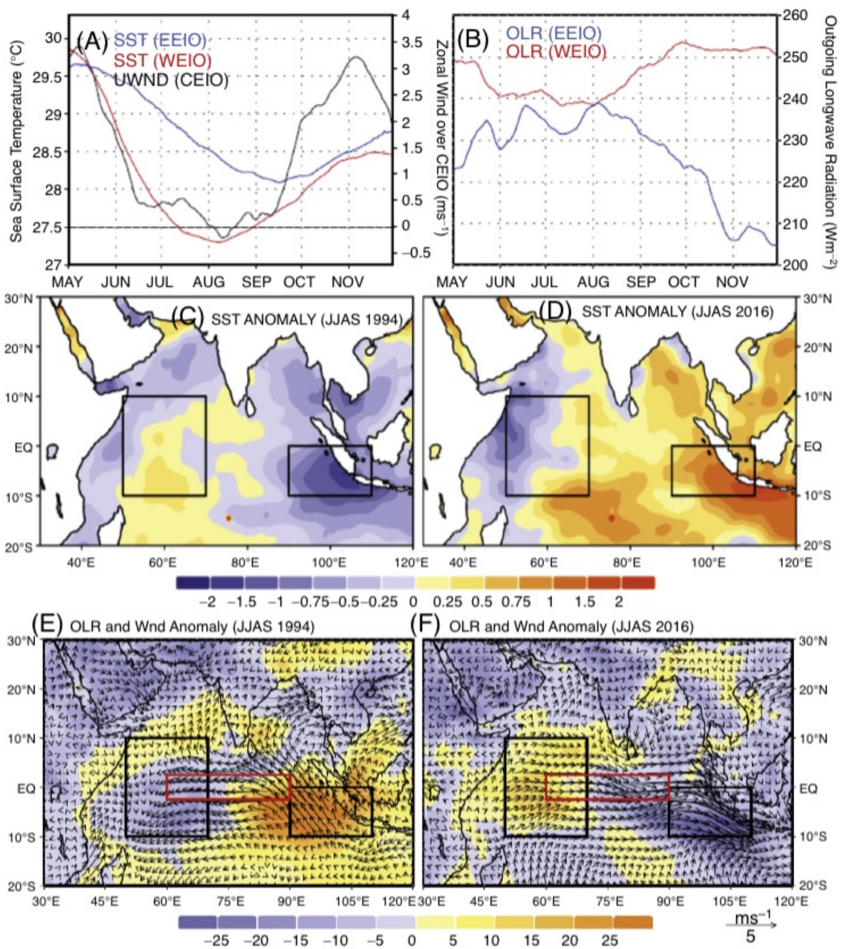
Large +ve IOD with Strong El Nino



Large +ve IOD without Strong El Nino



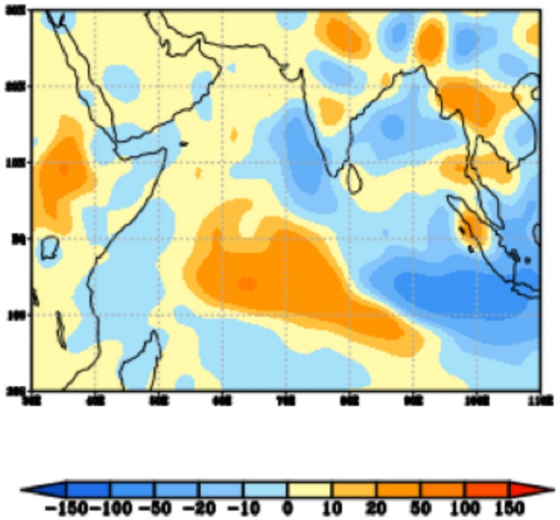
EQUINOO



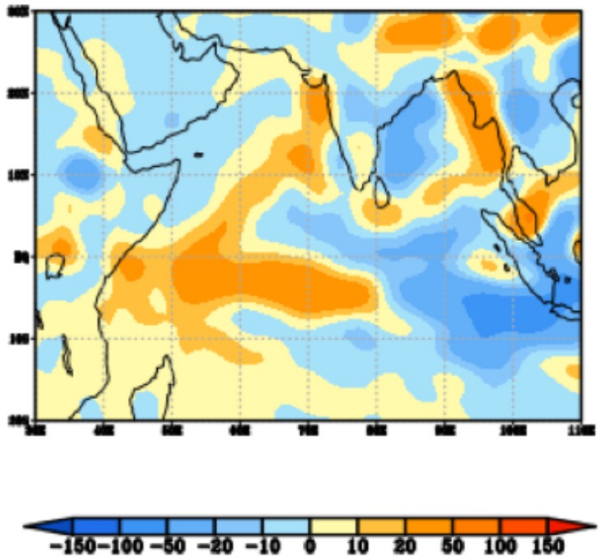
EQUINOO is considered to be the atmospheric component of the coupled IOD mode, it is not as tightly coupled to the ocean component of IOD.

June to September mean OLR/OLR anomaly (left) and mean SST/SST anomaly (right) patterns. Top: climatological mean for the period 1982–2010; middle: anomalies of 1987 and bottom: anomalies of 1988. Red contour in (A) encompasses the regions with SST above 27.5°C. SST data are based on HadISST (Rayner et al., 2003

IOD modoki years



Dipole years



Key Questions?

- What are the regional and local circulation responses to changes in spatial structure of atmospheric heating over the Indian Ocean ?
- How do these circulation changes in turn influence precipitation over India?
- Are the spatial structures of the dominant modes of heating insert a similar or different impact on rainfall and circulation?

What and why diabatic heating?

$$\Pi = \left(\frac{p}{p_0}\right)^{R/c_p}$$

- **Thermodynamic Equation**

$$c_p\Pi\left(\frac{\partial\theta}{\partial t} + \vec{\nabla}\cdot(\vec{v}\theta) - \theta(\vec{\nabla}\cdot\vec{v}) + \omega\frac{\partial\theta}{\partial p}\right) = Q + Q_{add}$$

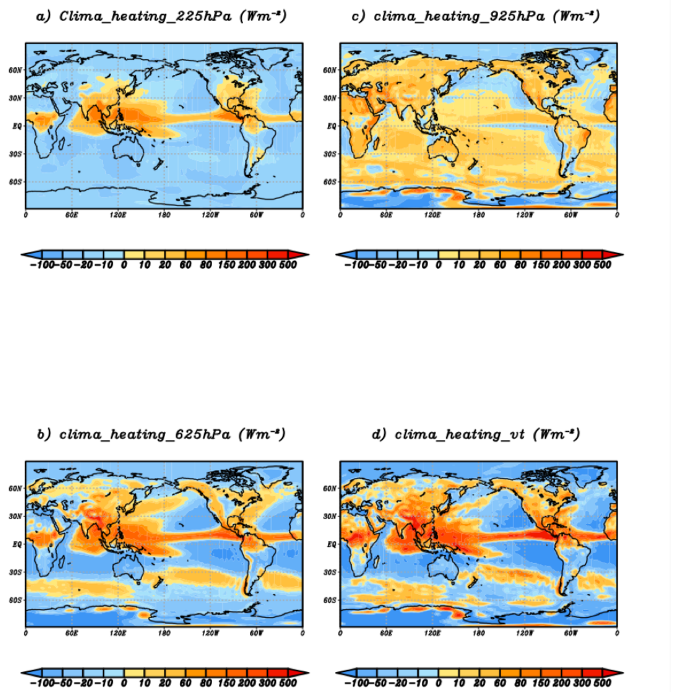
- Q comprised of latent, sensible and radiative heating/cooling

- Added heating modeling technique simply adds a term Q_{add} and model adjusts
- Benefit of preserving internal feedbacks with heating (unlike relaxation or prescription)

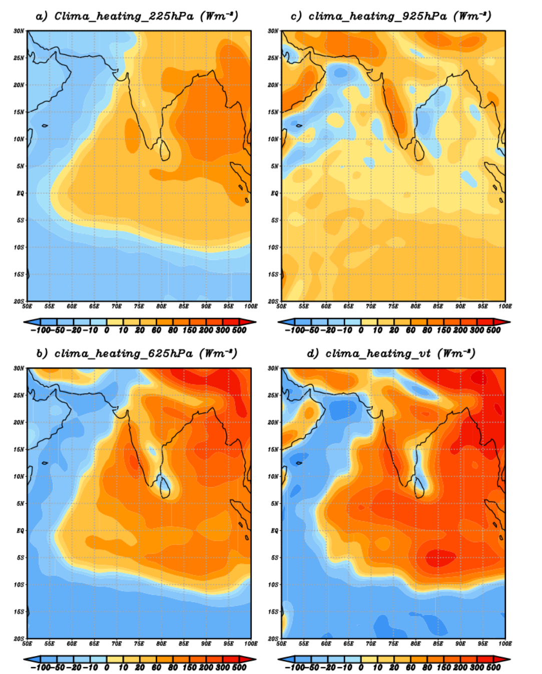
- In tropical mid-troposphere, Q is dominated by latent heating from condensation (rainfall) and largely balanced by vertical motion

Past studies mostly focus on the role of SST anomalies in teleconnections, often neglecting the critical linkage in atmospheric diabatic heating. Diabatic heating may be considered more physically relevant in that it directly generates upper-tropospheric vorticity and a resultant Kelvin and Rossby wave response (Gill, 1980) that generally gives rise to teleconnections. Thus, understanding the response to tropical diabatic heating on monsoon circulation a primary motivation for this present study

Global Climatological JJAS Diabatic heating Watt/m2

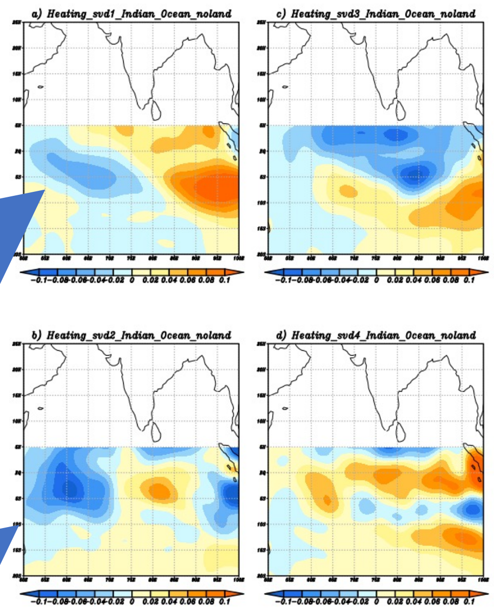


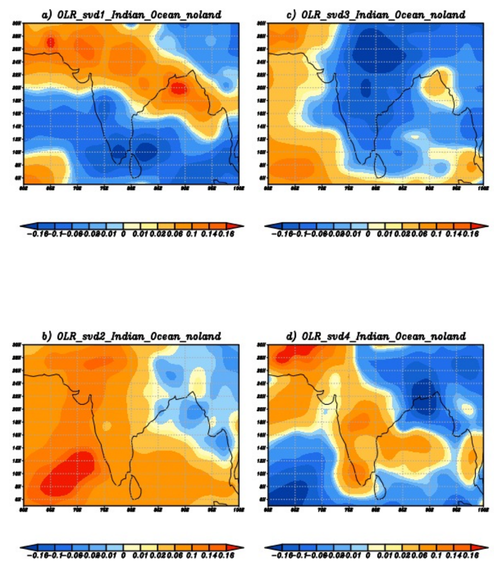
Regional Climatological JJAS Diabatic heating Watt/m2



Dominant modes in heating

Mode	SCF(%)	CSCF(%)	Pearson's Correlations
1	57.4	57.4	0.694
2	**24.9**	82.3	0.653
3	7.79	90.09	0.537
4	5.21	95.3	0.626





Maximum Covariance Analysis (MCA) is a multivariate statistical technique for identifying linear relationships between two variables (Bretherton et al., 1992; Wallace et al., 1992). The leading MCA mode is a unique pair of spatial patterns, whose temporal variation is described by a pair of time series termed the variates. The leading mode maximizes the squared covariance between the two variables. Trailing MCA modes consecutively maximize the remaining squared covariance such that pattern vectors are orthogonal and differing modes have zero covariance between each other.

Thermodynamic Equation + Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial}{\partial p}(\omega_a + \omega_d)$$

$$\omega_d = \frac{Q}{c_p \Pi \frac{\partial \theta}{\partial p}}$$

$$\frac{\partial \theta}{\partial p} < 0$$

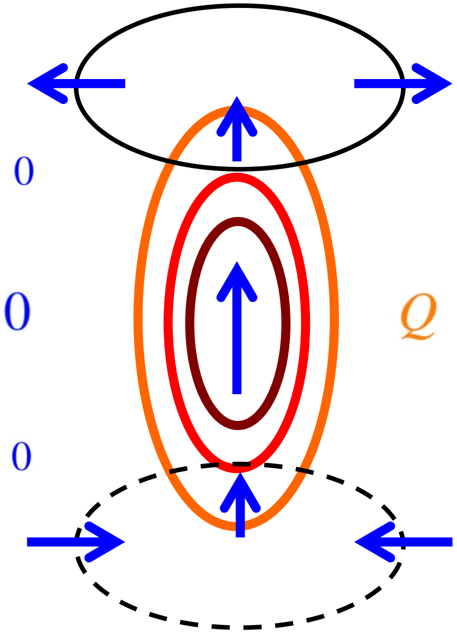
Mapes & Houze (1995)

Vertical gradient in heating
and vertical motion

→ divergence

→ vorticity (excitation of Rossby waves)

→ planetary-scale teleconnections

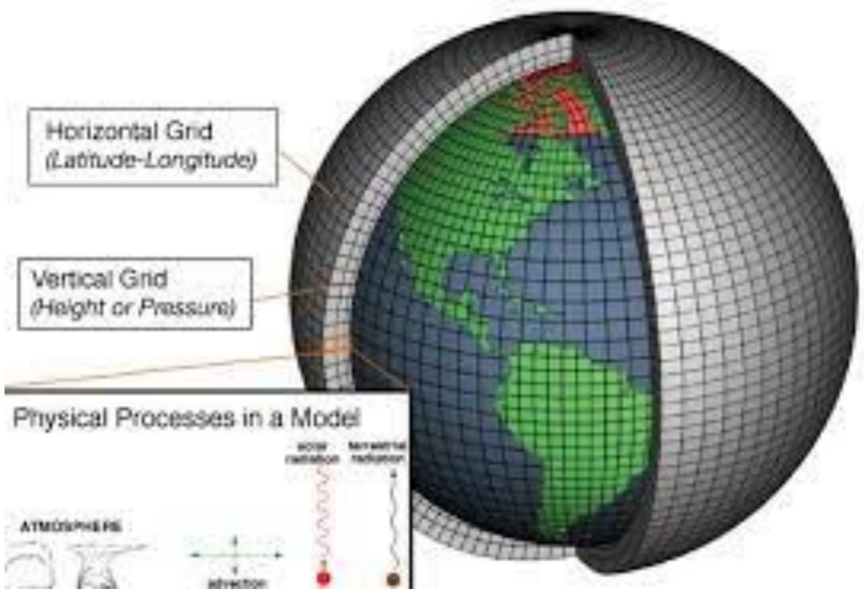


AMS-2022

COURTESY: Erik T Swenson

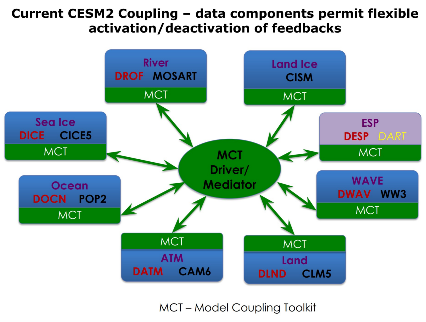
Model Descriptions and Experimental set up

A virtual laboratory for experimentation ….

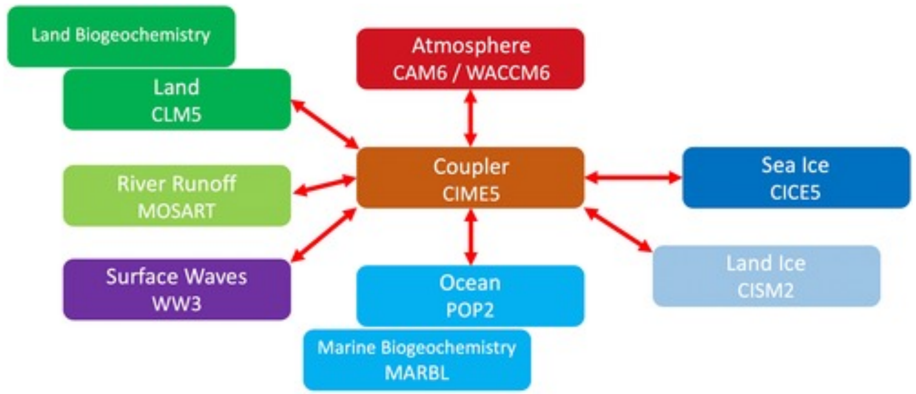


General purposes include:
- Providing scientific understanding of past observed events and changes

The Community Earth System Model (CESM) is a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.



Model and experimental design

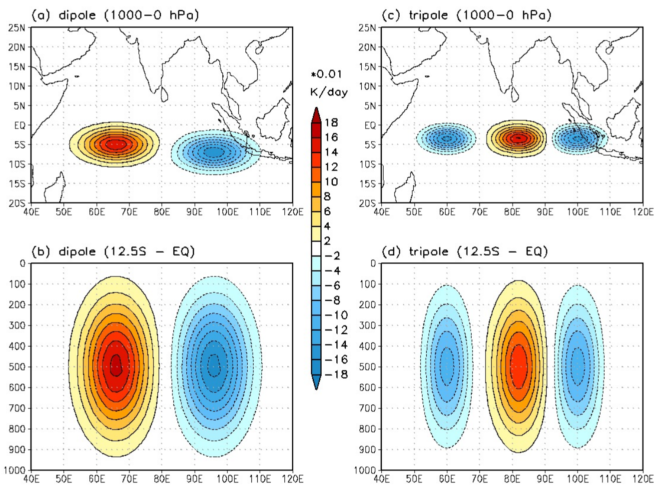


- Control run 70years
- Dipole exp 50years
  - +ve event case
  - -ve event case
- Tri-pole exp 50years
  - +ve event case
  - -ve event case

- Doubling –Dipole exp 50years
- Asymmetric heating exp 50years

We ran cesm2.0.0 (CAM5 atmosphere) at 1degree horizontal resolution in the atmosphere, coupled with 1850 forcing (however CO_2 was changed to more modern day 368.9 ppm).

CAM5 possesses significant modifications compared with CAM4, with a range of improvements to its representation of physical processes. It includes a new shallow convection scheme a stratiform cloud microphysical scheme, an updated radiation scheme, and a three-mode modal aerosol scheme (MAM3). The default number of vertical levels in CAM4 is 26, whereas it is 30 in CAM5



Steady idealized heating/cooling that is directly added to CESM2 (plotted in units of 0.01 K/day). In (a) is the horizontal variation of the vertical average (1000 – 0 hPa) dipole heating. In (b) is the vertical vs. zonal variation of the latitudinal average (12.5S – Eq.) dipole heating. In (c) and (d) is the same, but for the tripole heating.

Dominant modes in heating

Mode	SCF(%)	CSCF(%)	Pearson's Correlations
1	57.4	57.4	0.694
2	24.9	82.3	0.653
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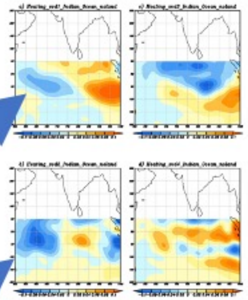
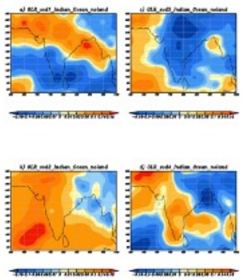
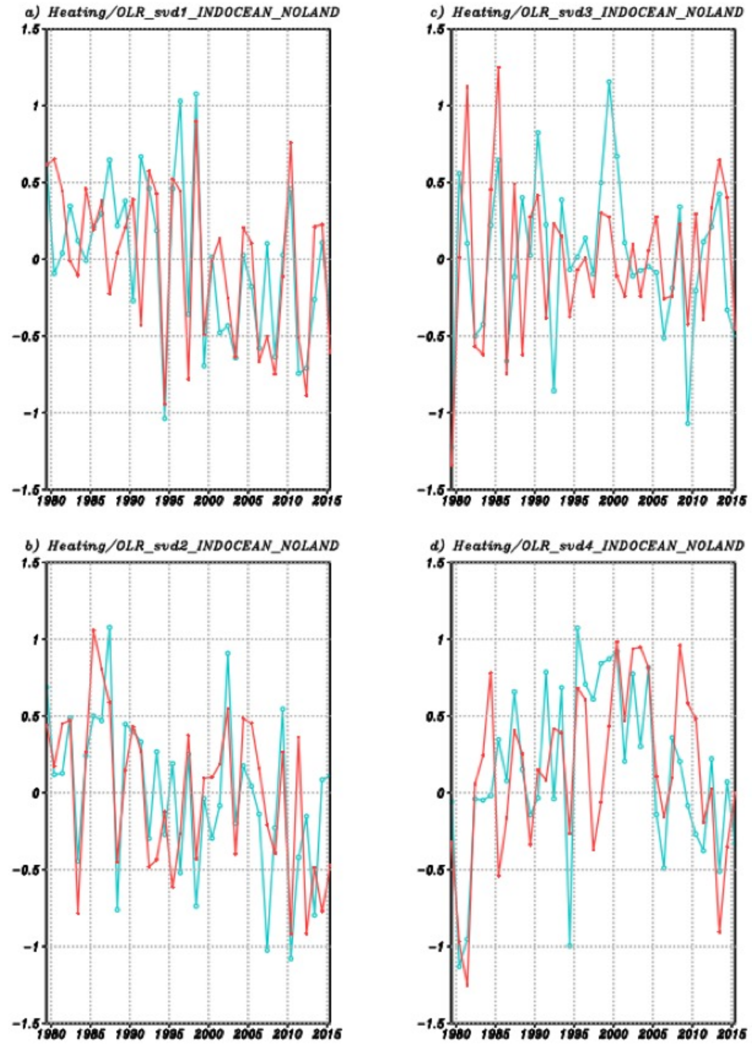
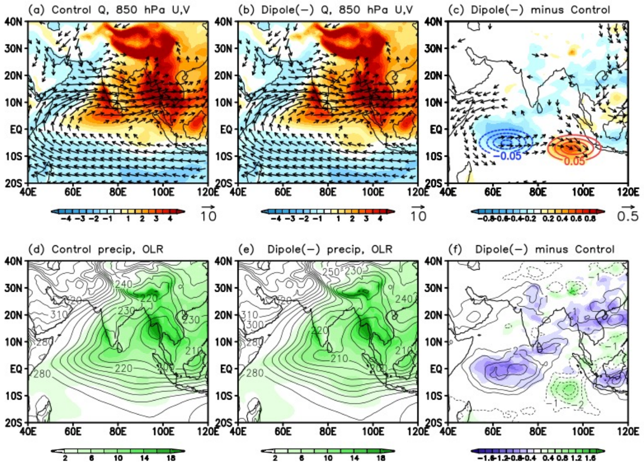








IOD -VE

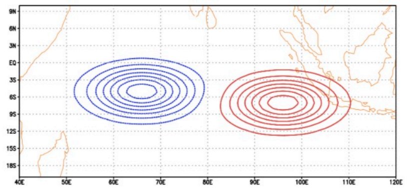
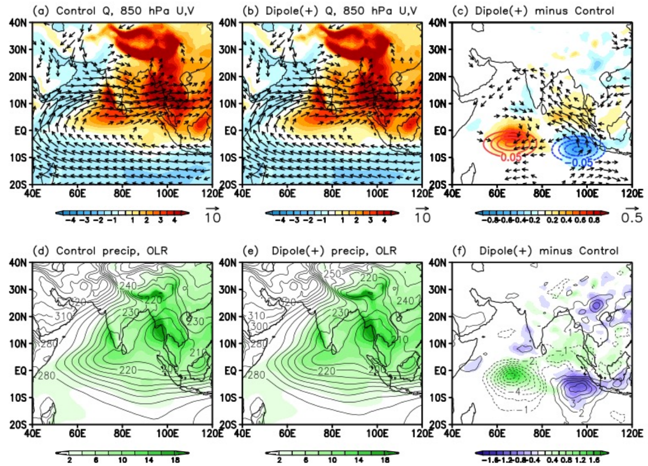


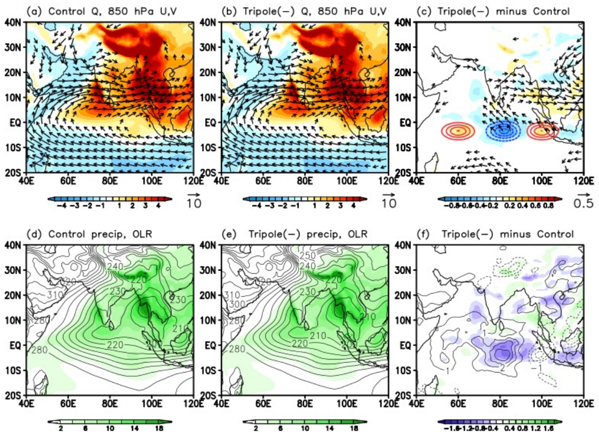
Figure 1:The boxes used to add heating/cooling for the model experiment for Positive and negative Dipole cases.



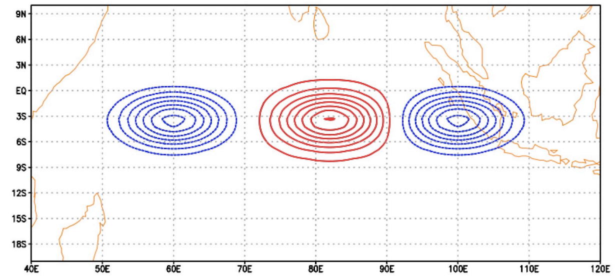
IOD +VE

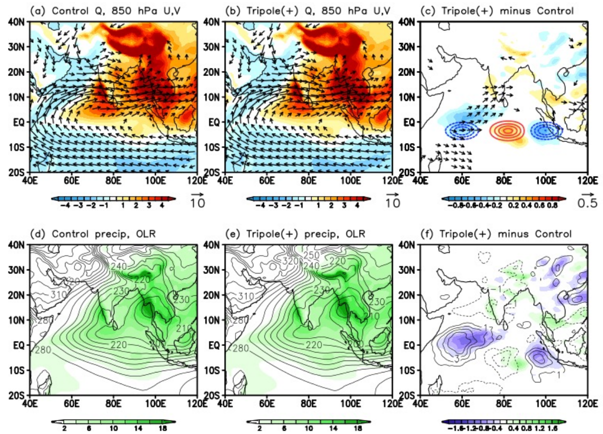
Results

June-September (JJAS) seasonal mean fields averaged over 50 years of CESM simulations centered over India and the tropical Indian Ocean. Vertically-averaged (850-50 hPa) diabatic heating rate (Q, K/day, shading) is shown along with 850 hPa winds (m/s, vectors) for (a) Control simulations and (b) Dipole (+) simulations, and for (c) the difference. Also shown are precipitation (m/day, shading) and outgoing longwave radiation (OLR, W/m , contours) for (d) Control simulations and (e) Dipole (+) simulations, and for (f) the difference. In (c) and (f), only significant differences are shaded (using a 95% confidence interval)



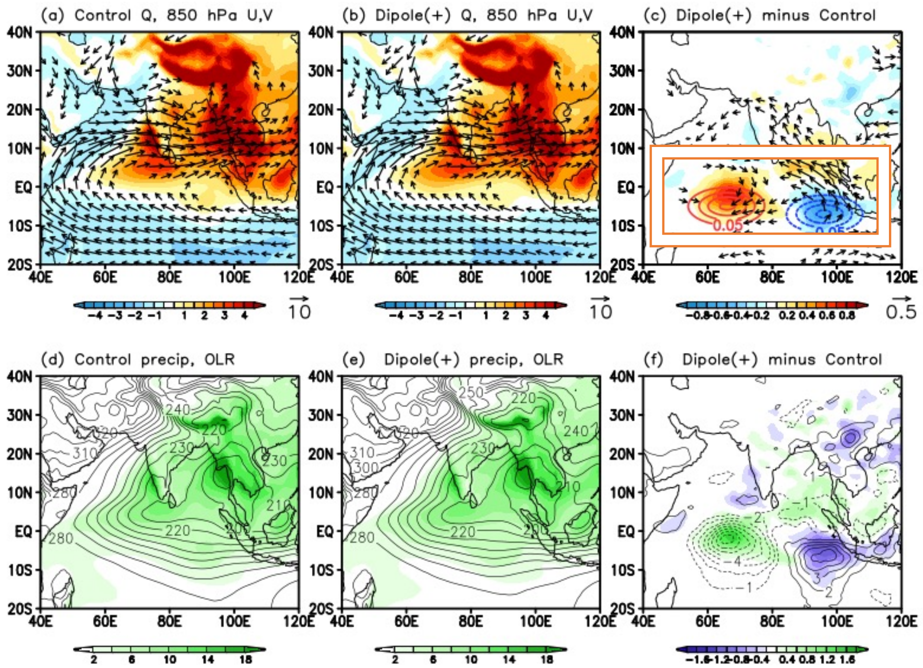
IOT -VE



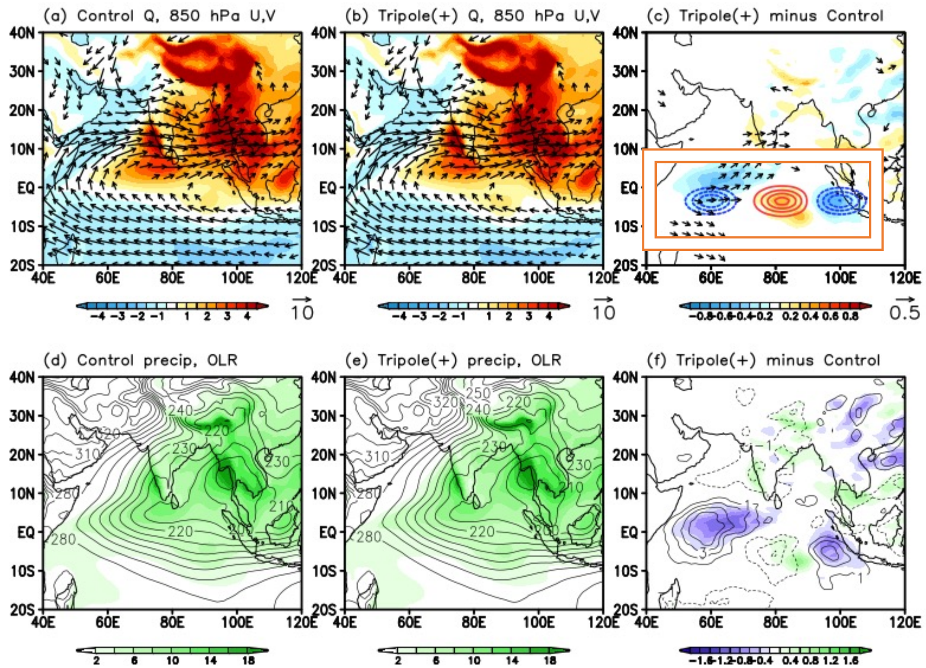


IOT +VE

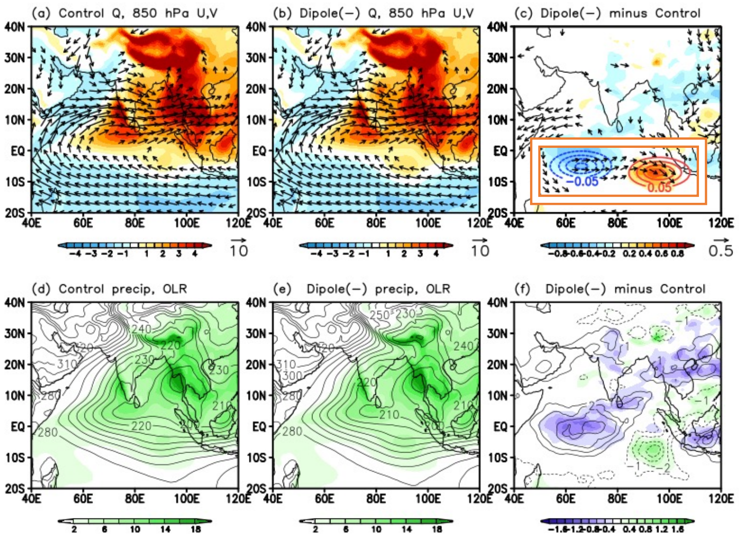
Results



Tripole_forcing

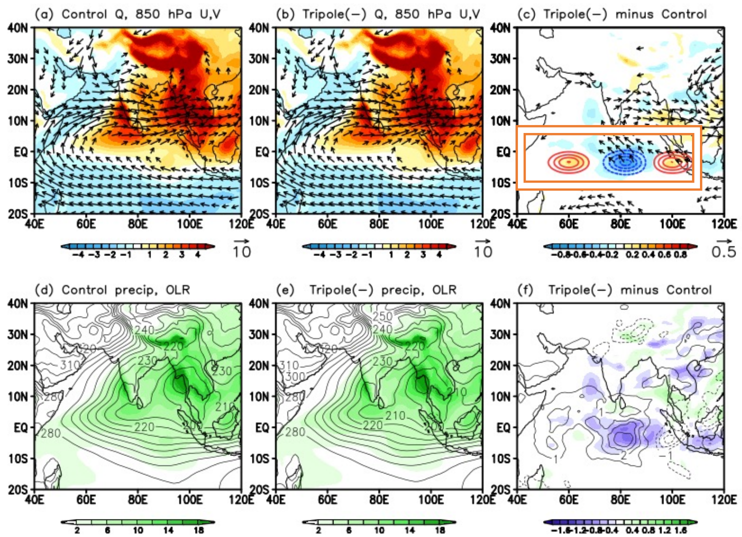


Dipole_forcing

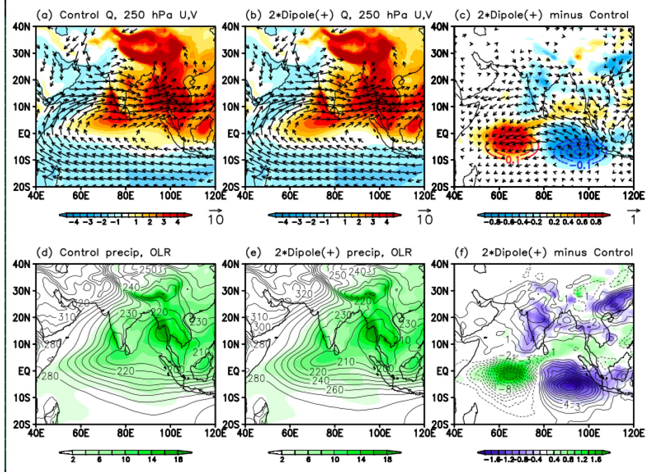


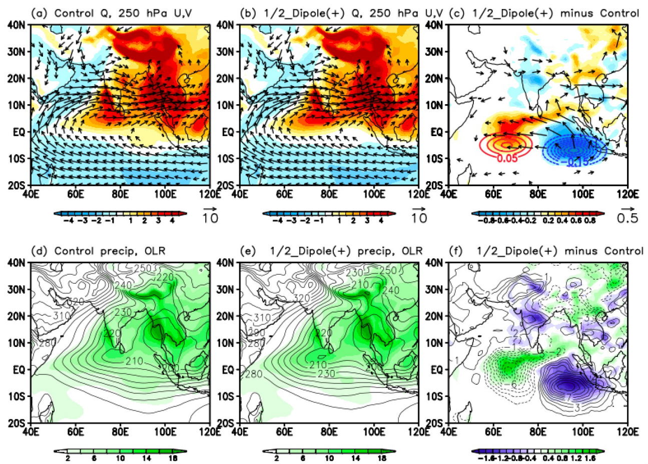
Dipole_forcing

Tripole_forcing

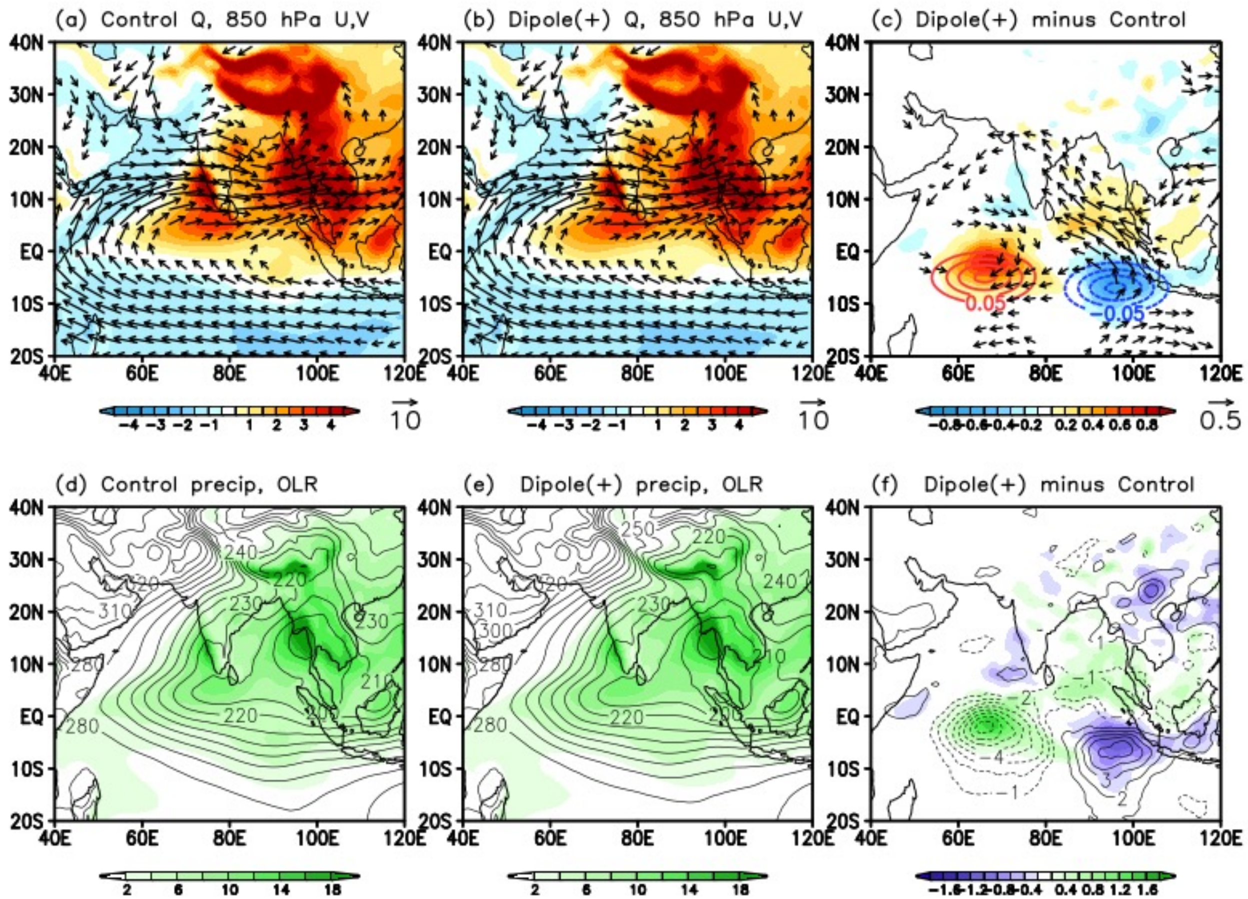


2*Dipole forcing



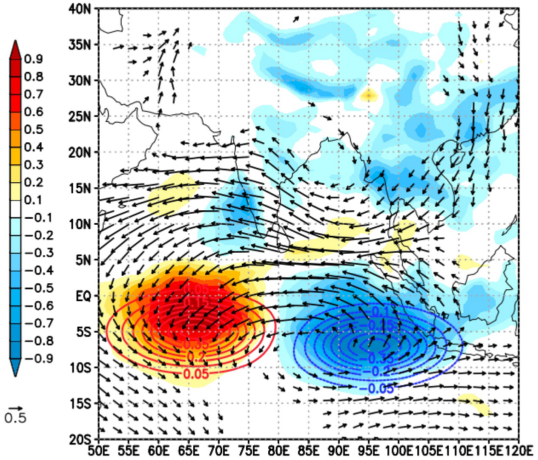


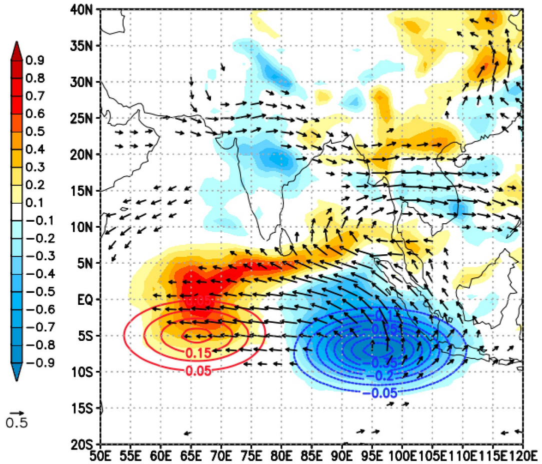
1/2_Dipole forcing



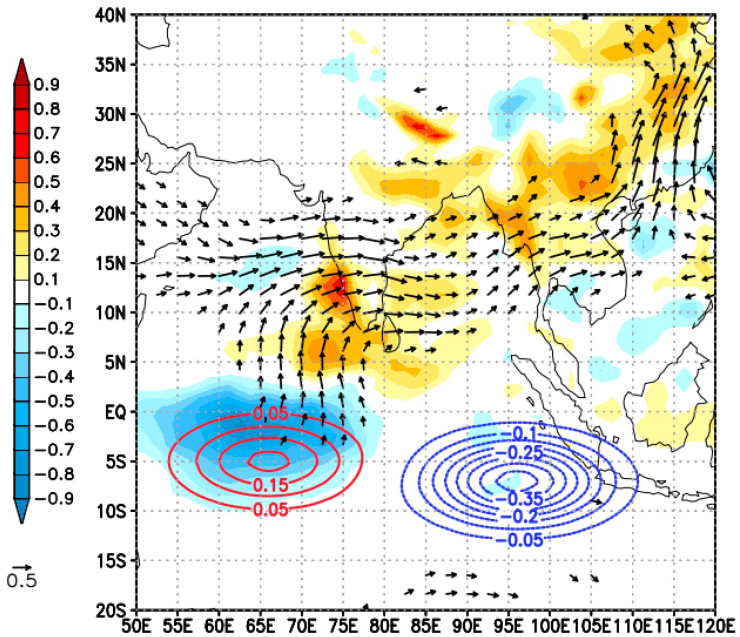
Dipole forcing

2*Dipole forcing





1/2_Dipole forcing



Difference: (1/2_Dipoleforcing minus 2*Dipole forcing

Key Findings

- circulation anomalies over Indian Monsoon region forced by two dominant mode of heating (Dipole and tri-pole) are distinct and distinguishable.
- spatial structure, extent, and magnitude of atmospheric heating and cooling anomalies over the Tropical Indian Ocean can influence the degree to which a monsoon type response is triggered.
- heating structure is an influential center of action which explains the regional convection and precipitation during summer monsoon months.
- We note that if excess heating/cooling is imposed in the western Indian Ocean, the monsoon responds opposite to what is observed in CESM.

Goal:

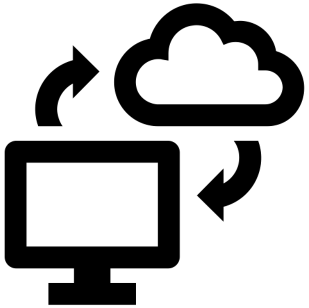
- **improve the seasonal to sub-seasonal predictability of summer monsoon variability**
- **Better seasonal prediction of Indian Ocean Dipole Mode (IOD and EQUINOO) like events**

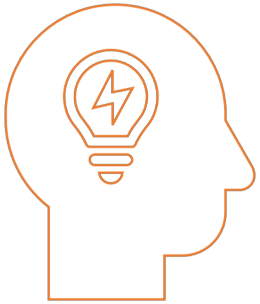
- **Understanding the mechanisms of the interannual variability is crucial for improving the monsoon forecasts.**

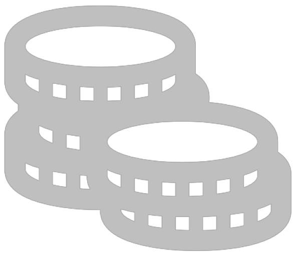
Key findings

- The results of this research may be summerized as follows:
  - Circulation anomalies over the Indian Monsoon region forced by two dominant modes of heating (Dipole and tri-pole) are distinct and distinguishable.
  - Surface wind anomalies associated with dipole and tripole mode over the equatorial Indian Ocean are different.
  - Spatial structure, extent, and magnitude of atmospheric heating and cooling anomalies over the Tropical Indian Ocean can influence the degree to which a monsoon type response is triggered. As the heating center location is different so it is expected to lead the changes in the zonal overturning circulation, known as the Walker circulation.
  - The heating structure is an influential center of action which explains the regional convection and precipitation during summer monsoon months.
  - We note that if excess heating/cooling is imposed in the western Indian Ocean, the monsoon responds opposite to what is observed in CESM.
  - In particular, accurate predictions of the IOD type and related impact on monsoon climate greatly enhanced the knowledge gap related to IMV and Indian ocean variability.

Limitation and Future Scope







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