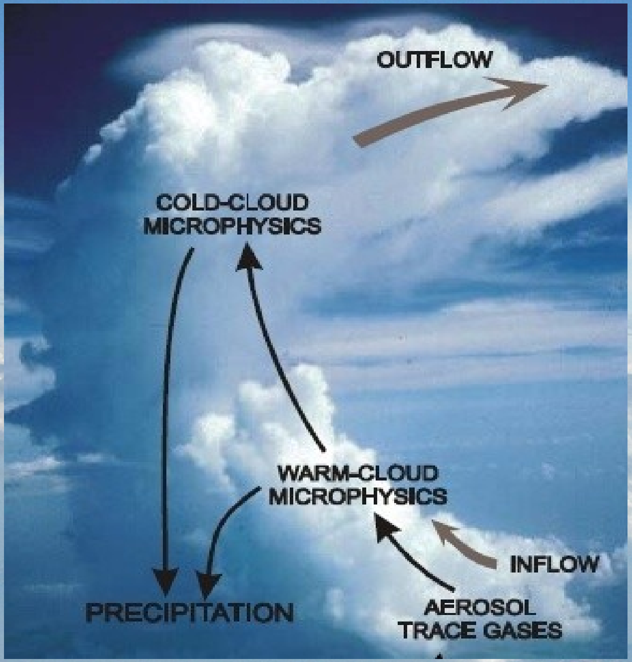
Cloud microphysical processes: A major challenge in global climate model in the perspective of Indian summer monsoon



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Background

Why we need skillful ISMR prediction?

- ✓ One fifth of the world's population living in South Asia thrives on regular arrival of the summer monsoon.
- ✓ **Agriculture, food production & economy critically depends on monsoon rain (Gadgil & Gadgil 2006).**
- ✓ Deficient and excess monsoon have great impact on the economy and life in general.
- ✓ **Skillful seasonal forecast has potential for high impact on agriculture and water resource management.**
- ✓ Therefore, a reliable forecast of monsoon rainfall on the subseasonal (i.e., active-break cycle) to seasonal time scale (S2S) is important.

Climate model and prediction of ISMR

- ✓ Coupled global land-atmosphere-ocean model is essential for the simulation of ISM climate (Wang et al., 2005).

- ✓ A dry bias in simulating JJAS precipitation over monsoon region is a generic problem (Rajeevan and Nanjundiah, 2009) and limits the skill.

Hope: Skill of present generation model (Rajeevan et al., 2012) higher than the earlier generation (models (Krishnakumar et al., 2005) → indicate that improvement of models lead to improvement of skill.

However, it remained a grand challenge. Even today all model skill is rather limited!!

Challenges in Simulating the mean of the Indian Monsoon and seasonal prediction:

- ❖ Conceptual basis for prediction skill beyond the limit of potential predictability

- ❖ Targeted improvement of Simulation and Prediction of the Indian monsoon

What is the role of cloud microphysics in Indian summer monsoon?

- **Sikka & Gadgil (1980) investigated on the maximum cloud zone (MCZ) over Indian sub-continent during summer monsoon.**

- **Wang et al. (2015) showed the cloud regime evolution in the Indian summer monsoon intraseasonal oscillations (ISO peaks and troughs).**

- **The vertical structure of cloud hydrometeors (e.g. cloud water and ice) associated with ISM are important (*Rajeevan et al. 2013*; *Halder et al. 2012*).**

- **Cloud hydrometeors also have a large impact on the vertical profile of latent heating (*Abhik et al. 2013; Kumar et al. 2014; Pokhrel et al., 2018*).**

- **The interaction among thermodynamics, cloud microphysics and dynamics plays a crucial role on the summer monsoon precipitating clouds (*Hazra et al. 2013a,b; Kumar et al. 2014*).**

- **The hydrological and radiative fluxes strongly linked with cloud microphysical processes (Baker 1997).**

Cloud microphysics

Cloud SAT: Cloud ice mixing ratio

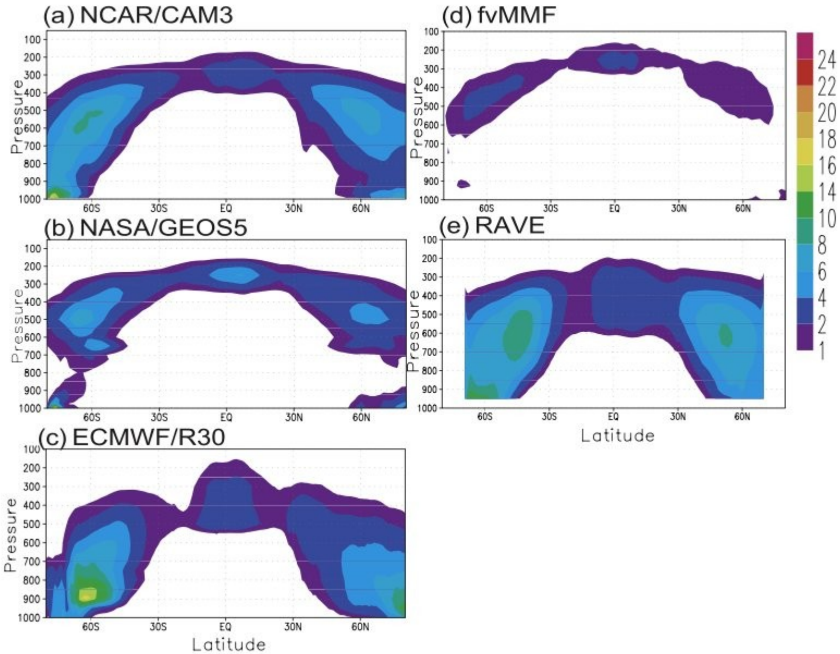
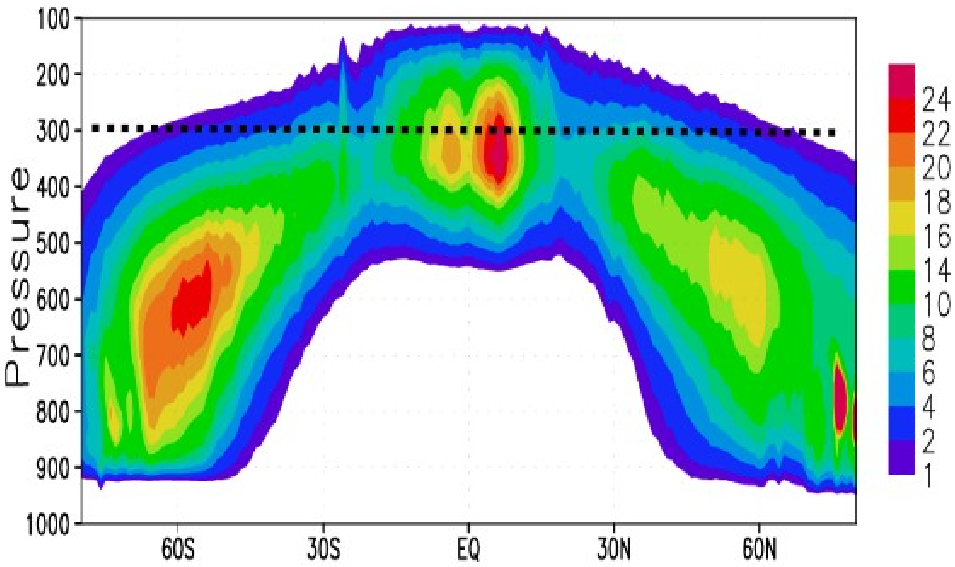


Figure 9. Annual and zonal mean values of cloud ice water content (IWC; mg m^{-3}) from (a) NCAR CAM3 (1979–1999), (b) NASA GEOS5 (January 1999 to December 2002), (c) ECMWF R30 analysis (August 2005 to July 2006), (d) fvMMF (July 1998 and January 1999), and (e) RAVE GCM (1998).



all most all models have difficulty in reproducing the observed IWC

Waliser et al., 2009

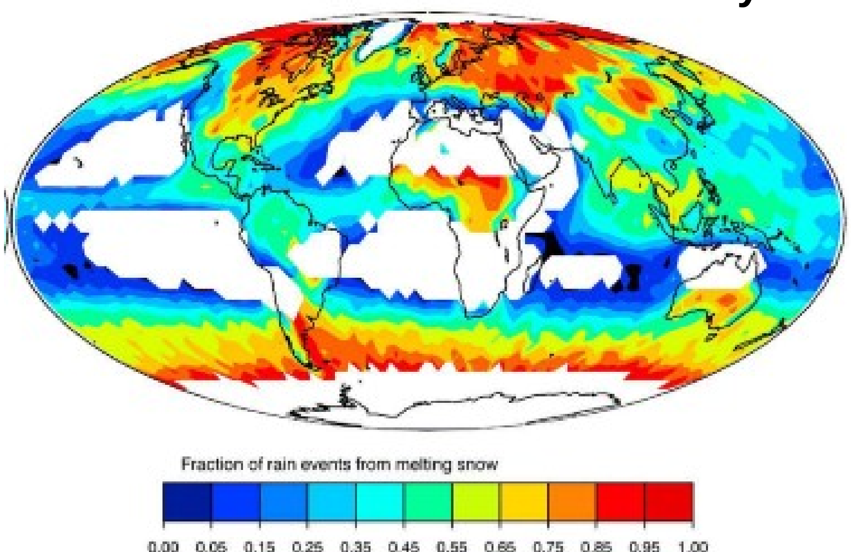
What is the role of microphysics & stratiform rain for ISM ?

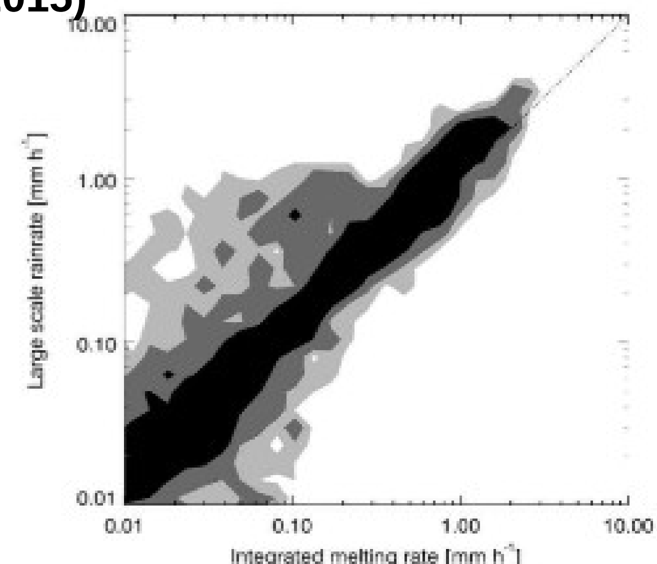
✓**Stratiform rain fraction plays a critical role in the organization of clouds and precipitation in MISOs [*Kumar et al.*, 2017].**

✓ **Vertical profile of heating as a result of increased contribution of stratiform rain fraction leads to better northward propagation of the MISO [Chattopadhyay et al., 2009; Choudhury & Krishnan, 2011].**

✓**Most climate models tend to produce too much convective precipitation and too little stratiform precipitation [*Sabeerali et al.*, 2013; *Saha, S. K. et al.*, 2014; *Hazra et al.*, 2015] as compared to the observations [Pokhrel and Sikka 2013].**

Field & Heymsfiled (2015)





Lack of organization of clouds and precipitation on MISO scale in model simulations is one of the major deficiencies in simulating the observed MISOs by climate models.

Hypothesis

A Model with high fidelity simulations of the MISOs will have high skill of Seasonal prediction of ISM.

Therefore: Target improving the biases in simulating the MISO in models. Potential double benefits:

- ✓ **It would reduce biases in mean simulation**
- ✓ **Improve skill of Seasonal Prediction**

Improve simulation of MISO ⟶ **Improve Mean ISM as well as skill of Seasonal Prediction**

Strategy

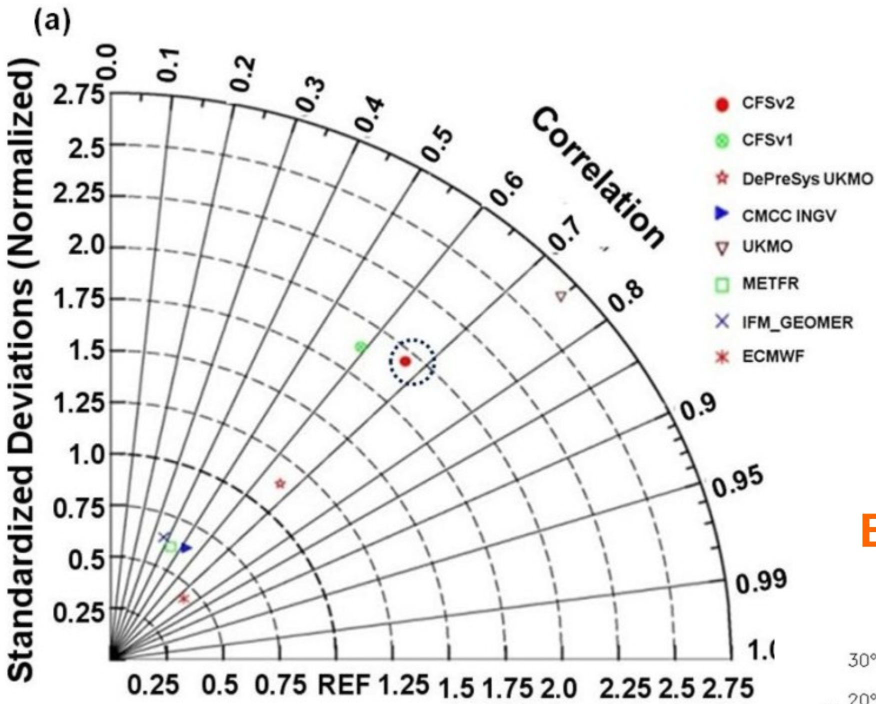
- ➢ Select a Prediction system involving A CGCM and make systematic improvement of physical processes on THAT CGCM (**one aspect**).
- ➢ The improvements on the CGCM will be targeted to improve the deficiency (bias) of the model in simulating Indian monsoon.

Under Monsoon Mission, We selected CFSv.2 as the base model for development and use in prediction of Indian Monsoon.

Why NCEP coupled forecast system (CFSv2) for Indian summer monsoon?

Major Biases of CFSv2

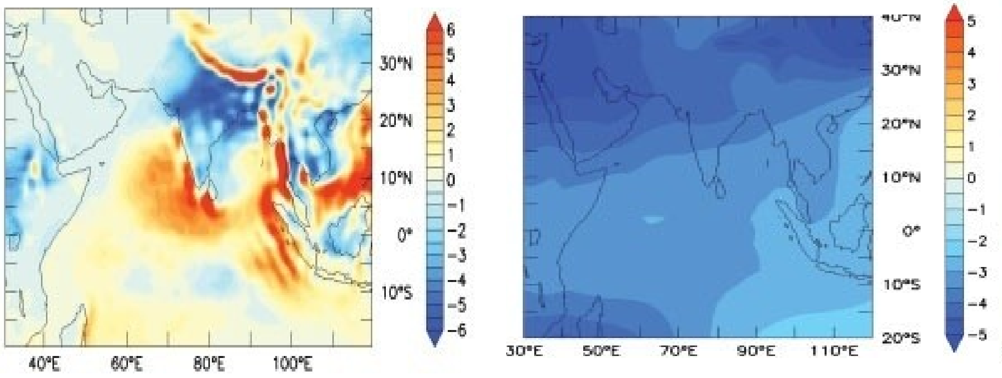
- ❖Surface rainfall: Dry bias
- ❖Tropospheric Temperature (TT): Cold bias



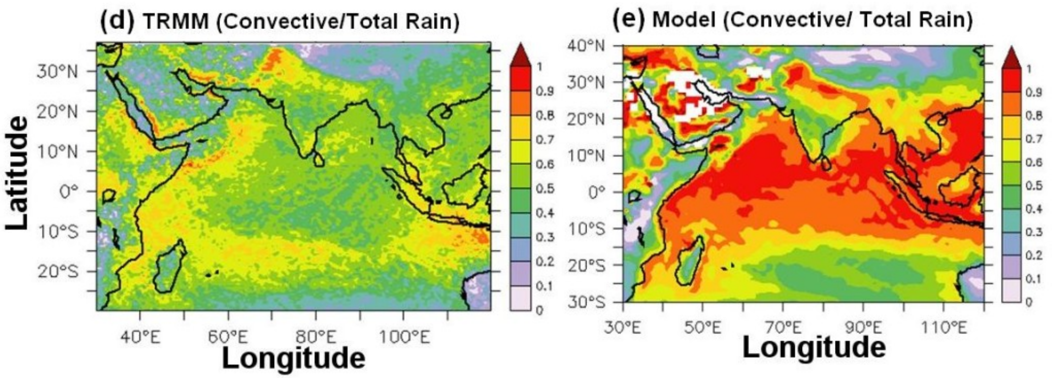
(a) Taylor plot showing the skill of models in simulating mean seasonal cycle over Indian land points.

Hazra et al. 2015b

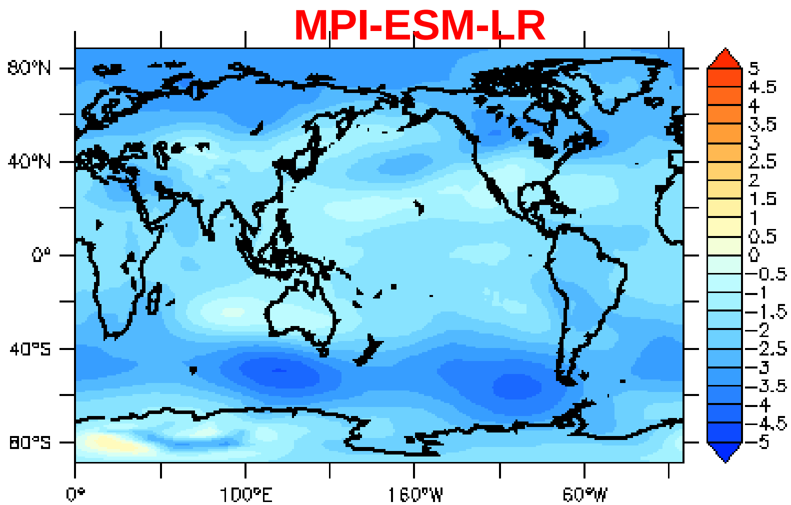
Model minus Observation

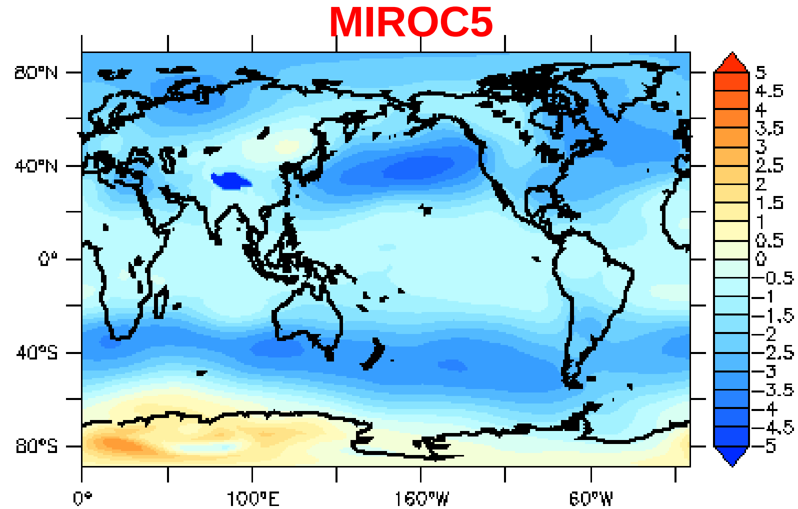


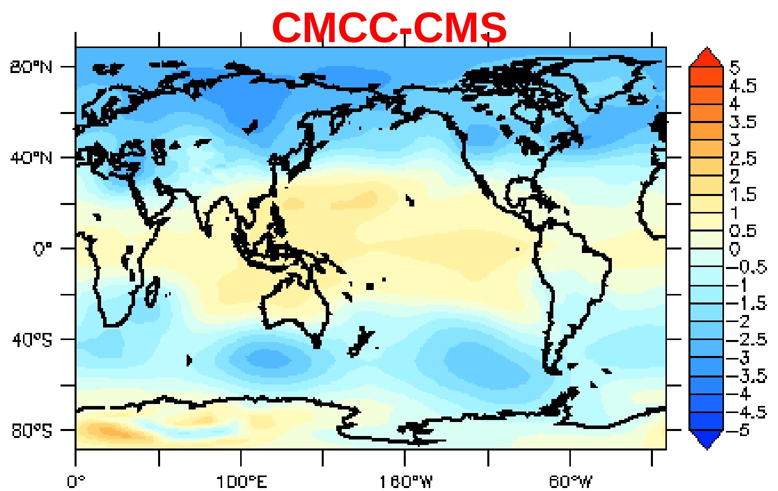
Bifurcation of convective and stratiform rain

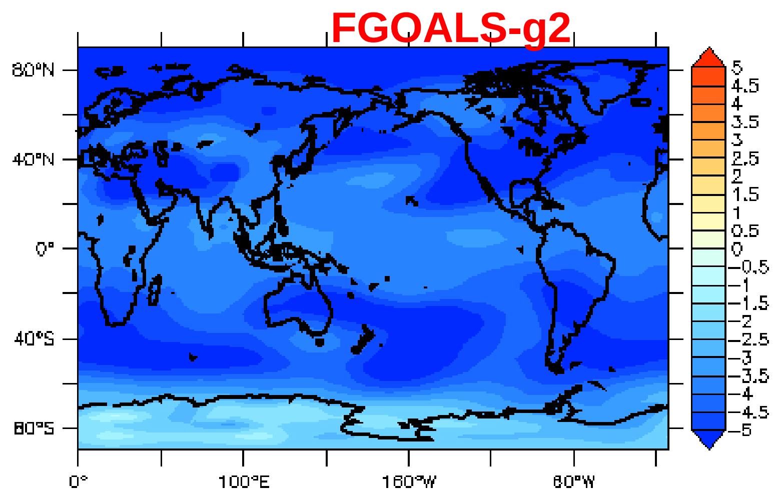


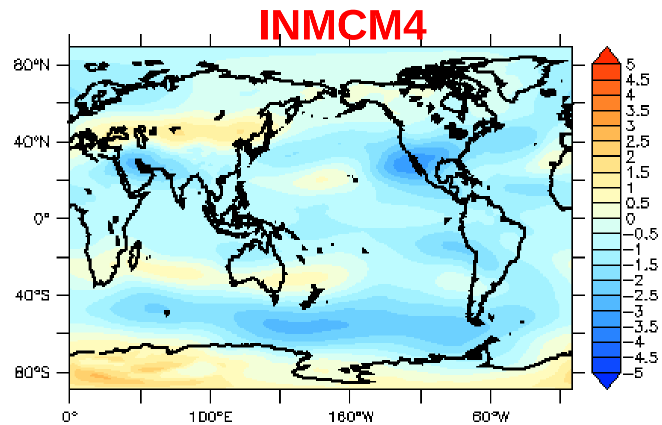
Saha et al. 2014





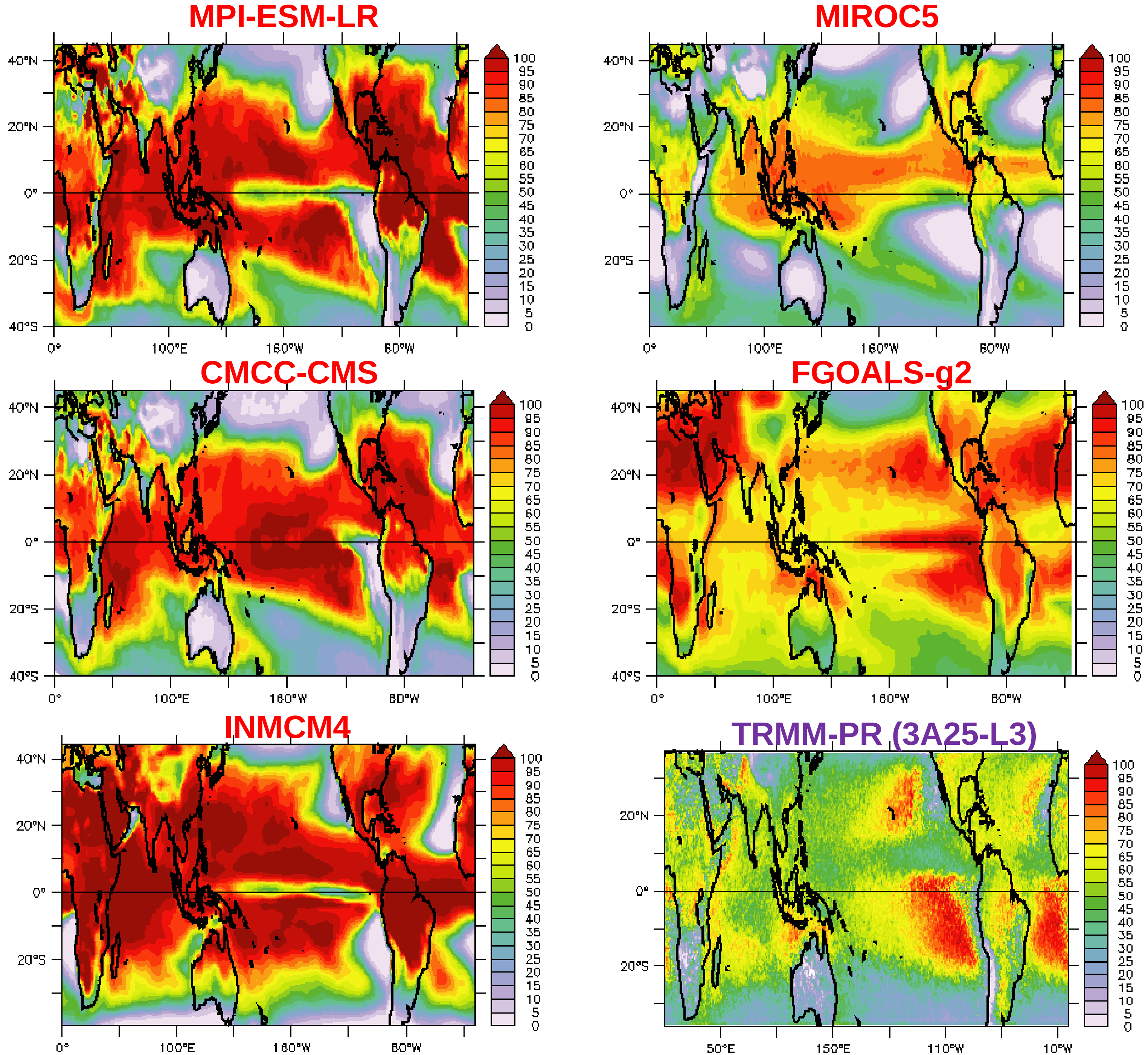




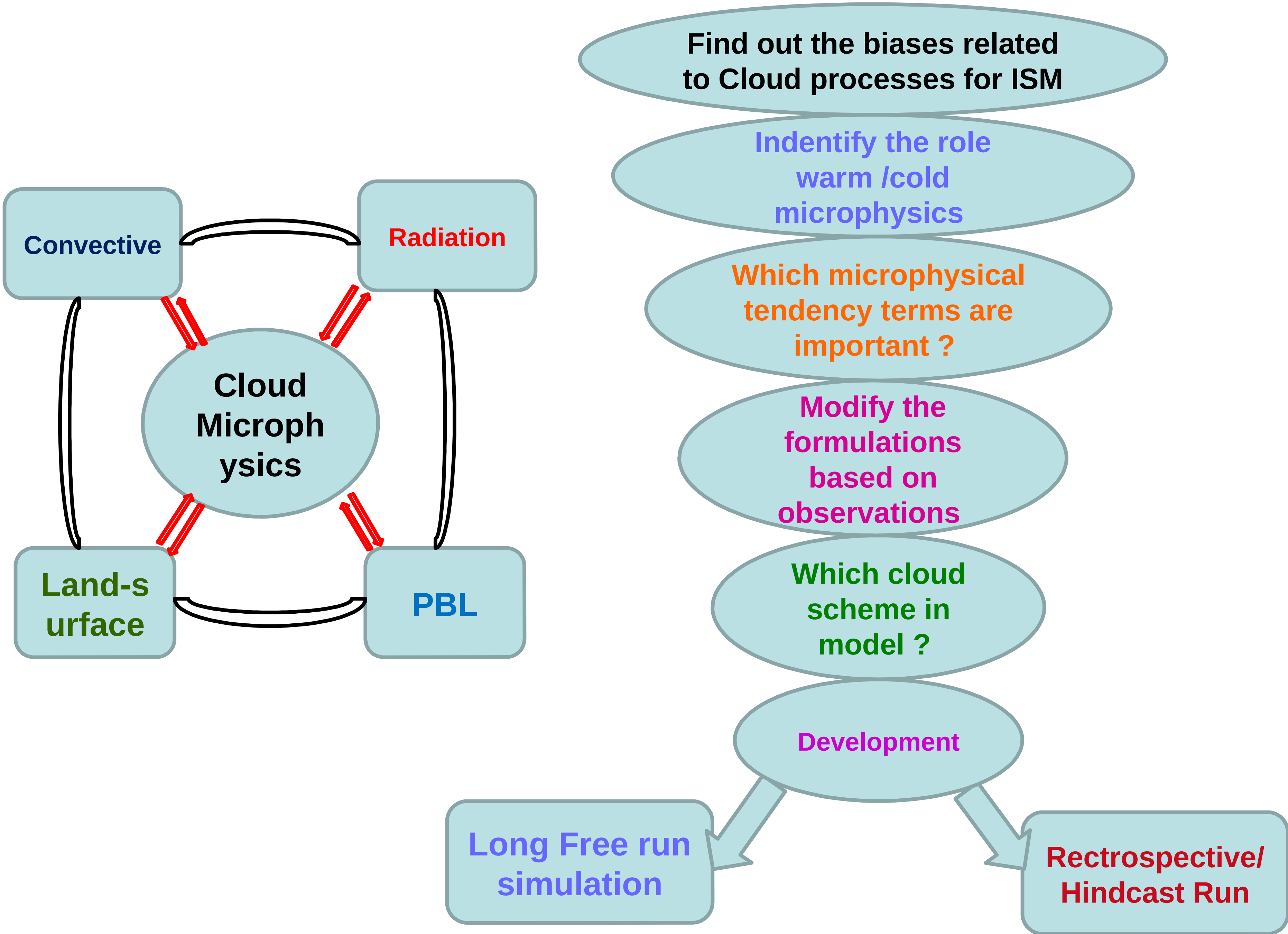


Tropospheric Temperature (TT) bias (averaged over 200 – 600 hPa) for CMIP5

Convective/Total Precipitation (JJAS Climatology)

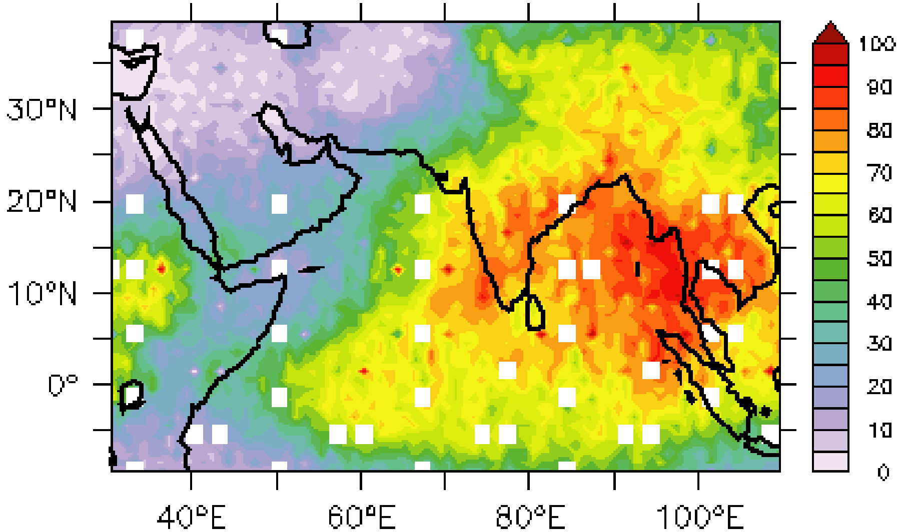


Flow chart of Model Development

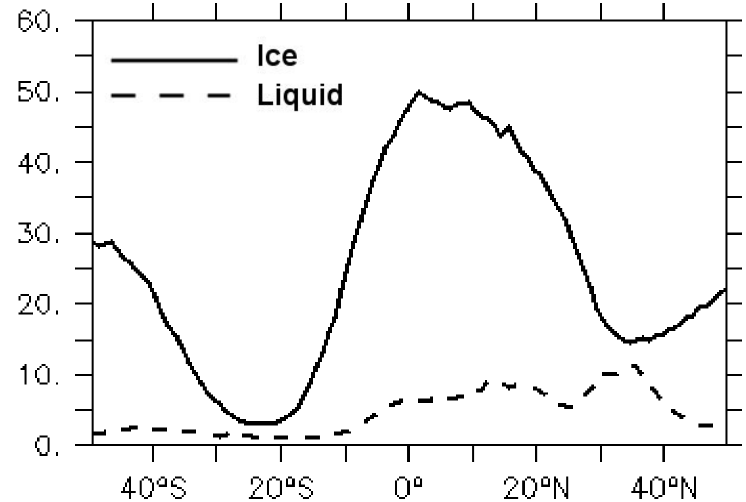


Cloud properties in NCEP CFSv2

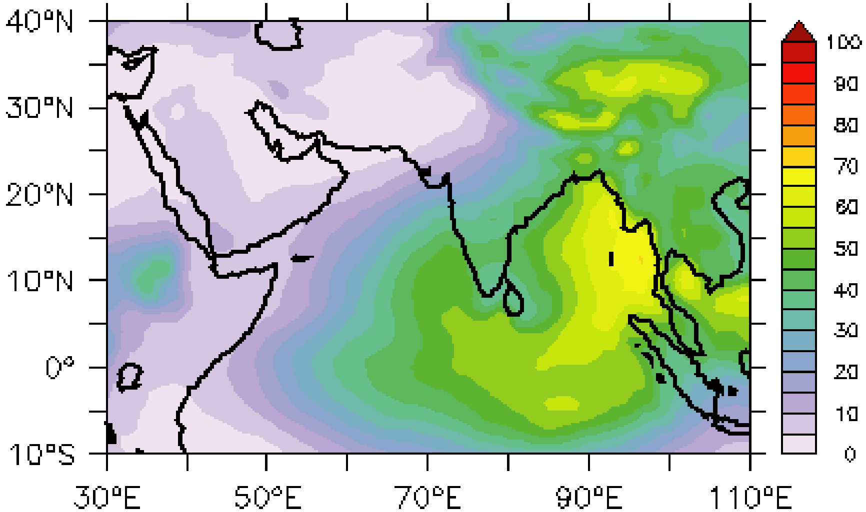
High Cloud Fraction (%) - CALIPSO



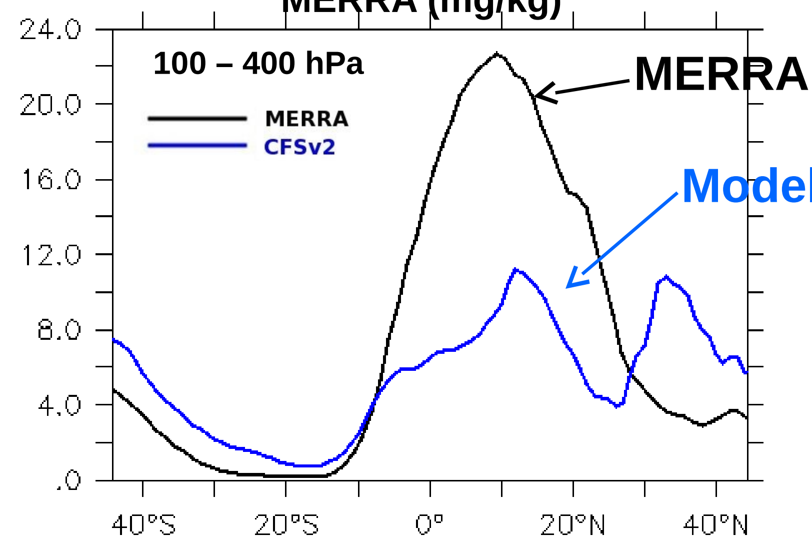
Phase (Ice or Liquid) of High Cloud Fraction (%) - CALIPSO



High Cloud Fraction (%) – CFSv2



Cloud condensate from CFSv2 and MERRA (mg/kg)

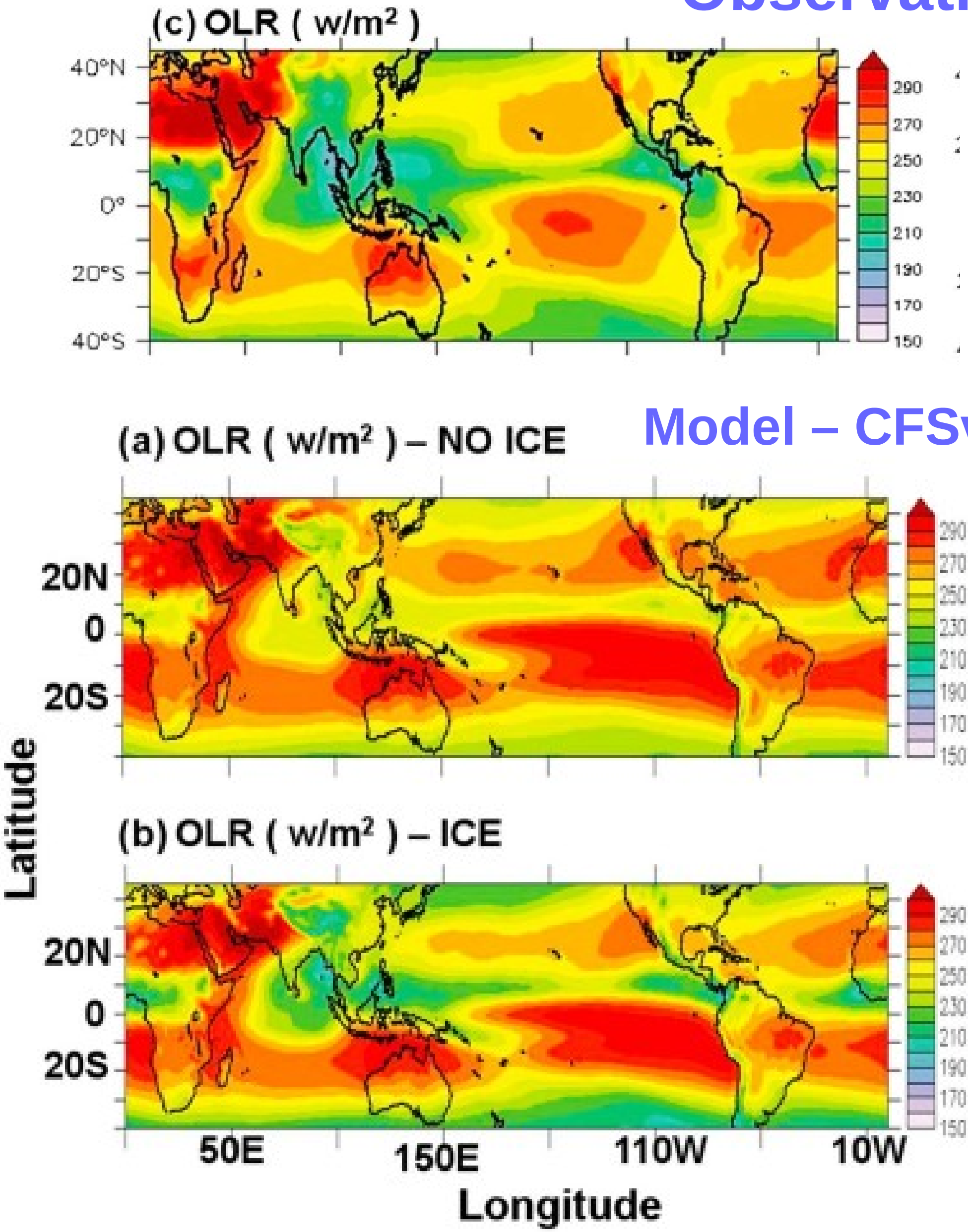


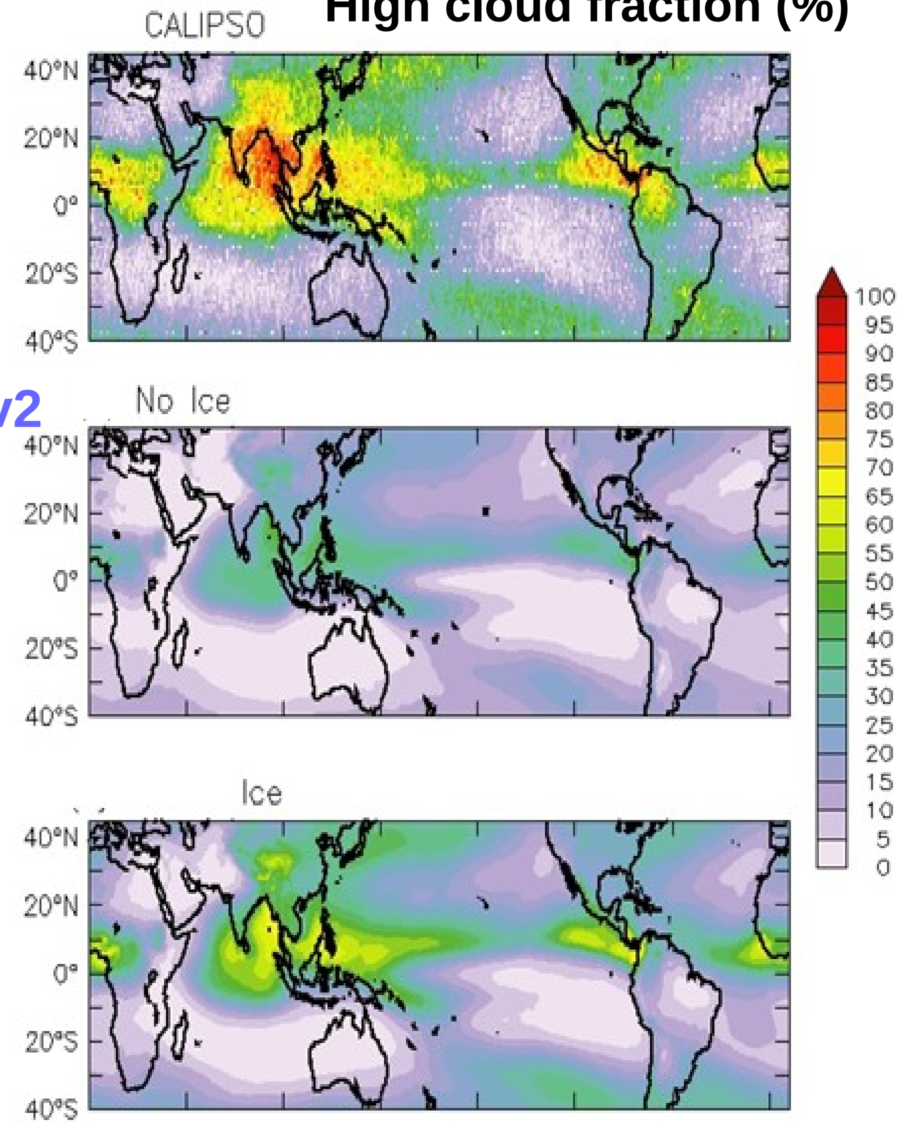
Hazra et al., 2015a

Basic understanding of warm and cold cloud microphysics in CGCM

Observation

Model – CFSv2



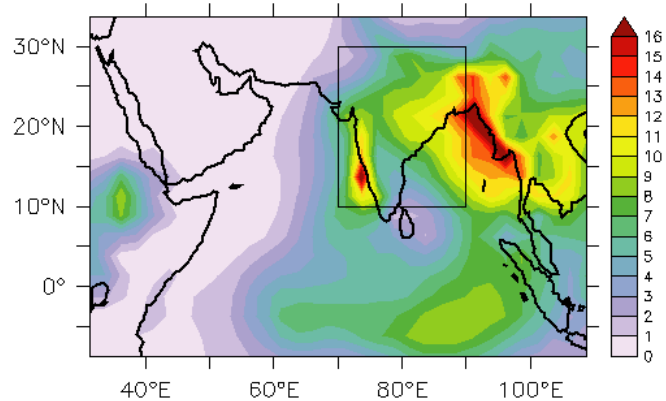


Hazra et al, 2017, JGR

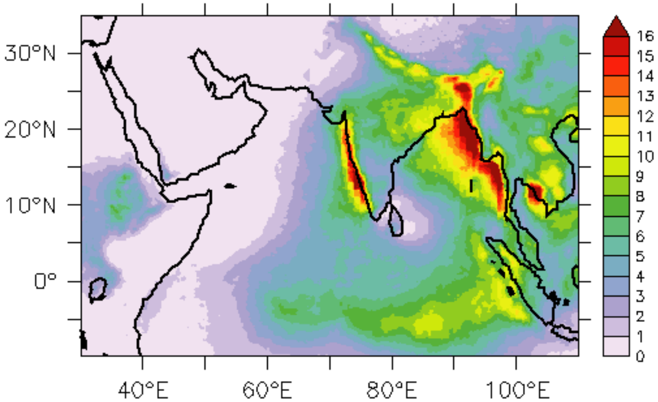
Which tendency equations in microphysical parameterization scheme should be targeted....

Role of Microphysical process rates (tendency terms) on ISM:

Precipitation - GPCP(mm/day)

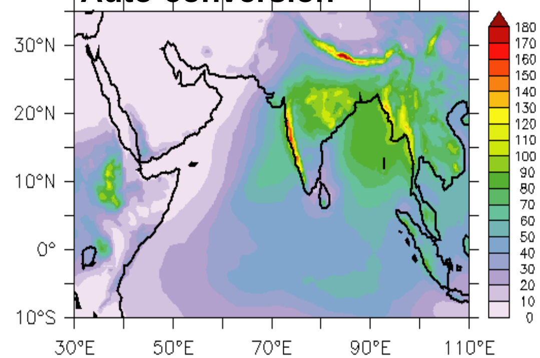


Precipitation – TRMM 3B42(mm/day)

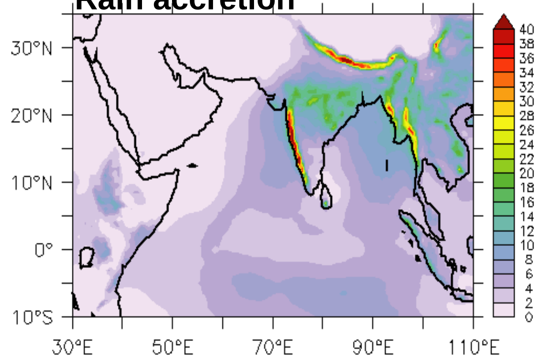


Tendency - MERRA (mg/m^2/s)

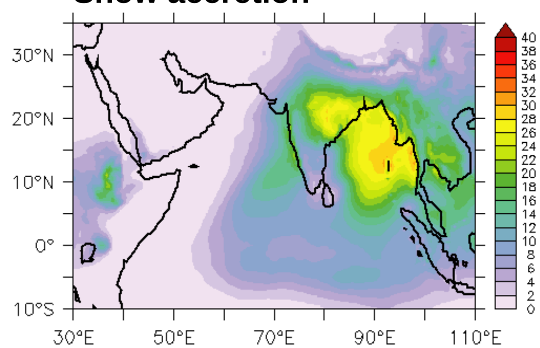
Auto-conversion

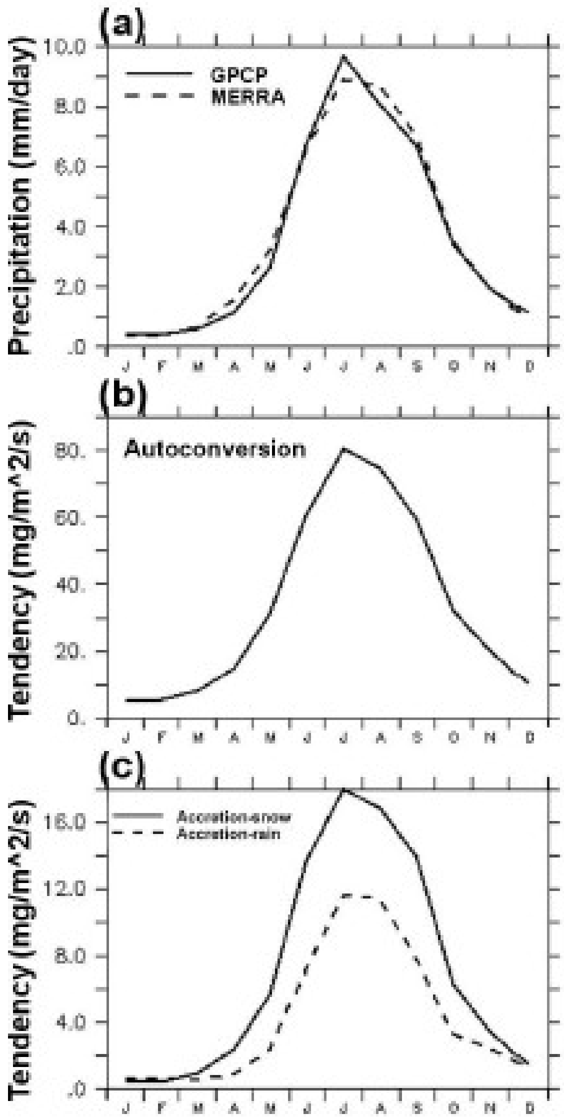


Rain accretion



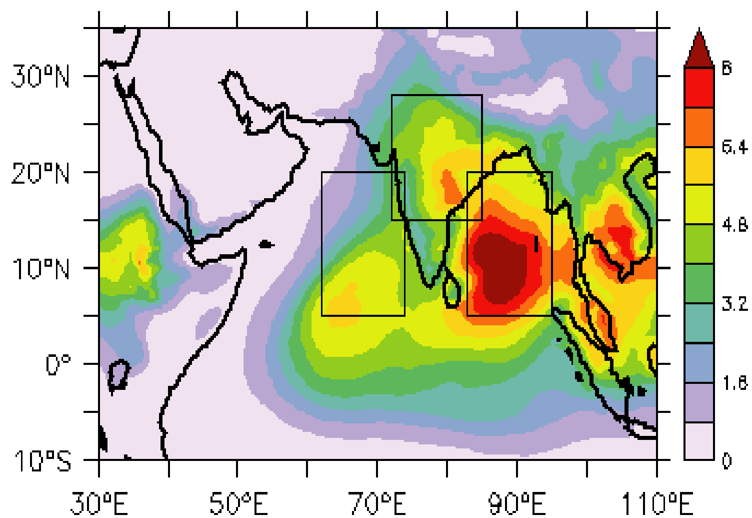
Snow accretion



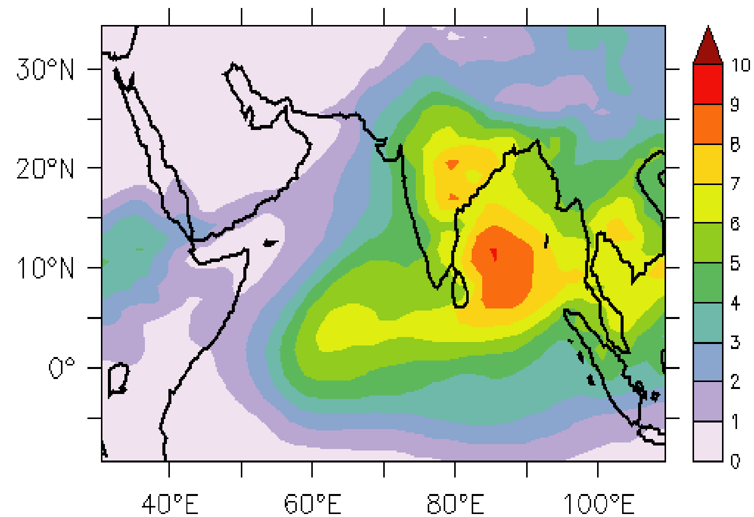


Hazra et al. (2016), Clim Dyn

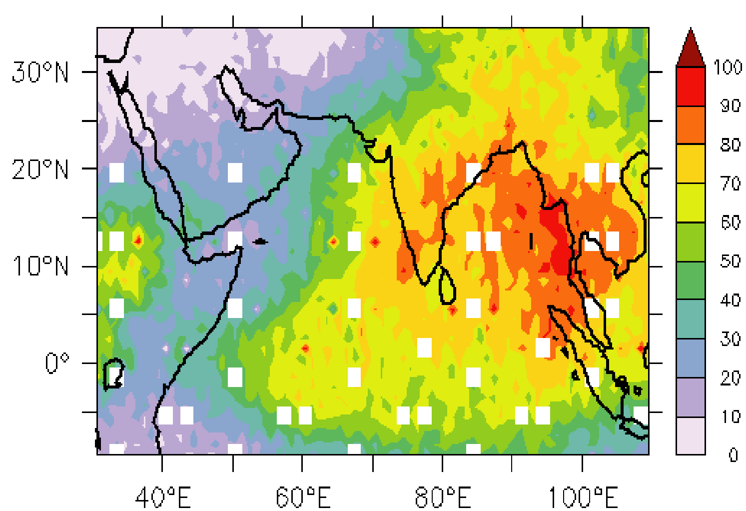
Freezing of cloud ice - MERRA (mg/m^2/s)



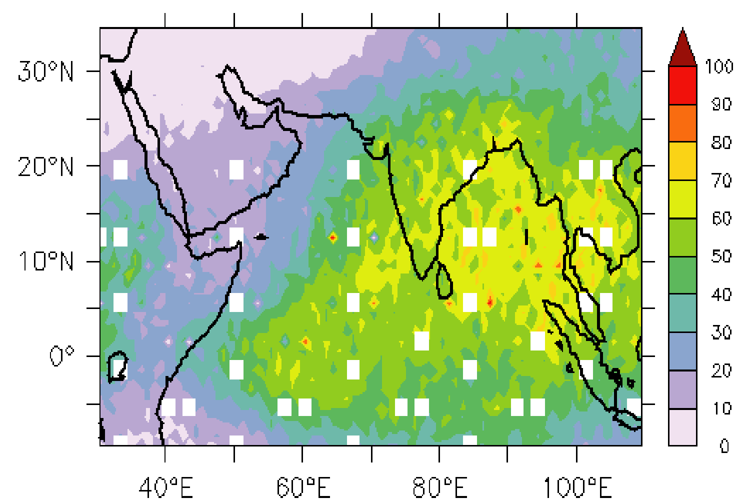
Cloud ice mixing ratio - MERRA (mg/kg)



High Cloud Fraction - CALIPSO (%)

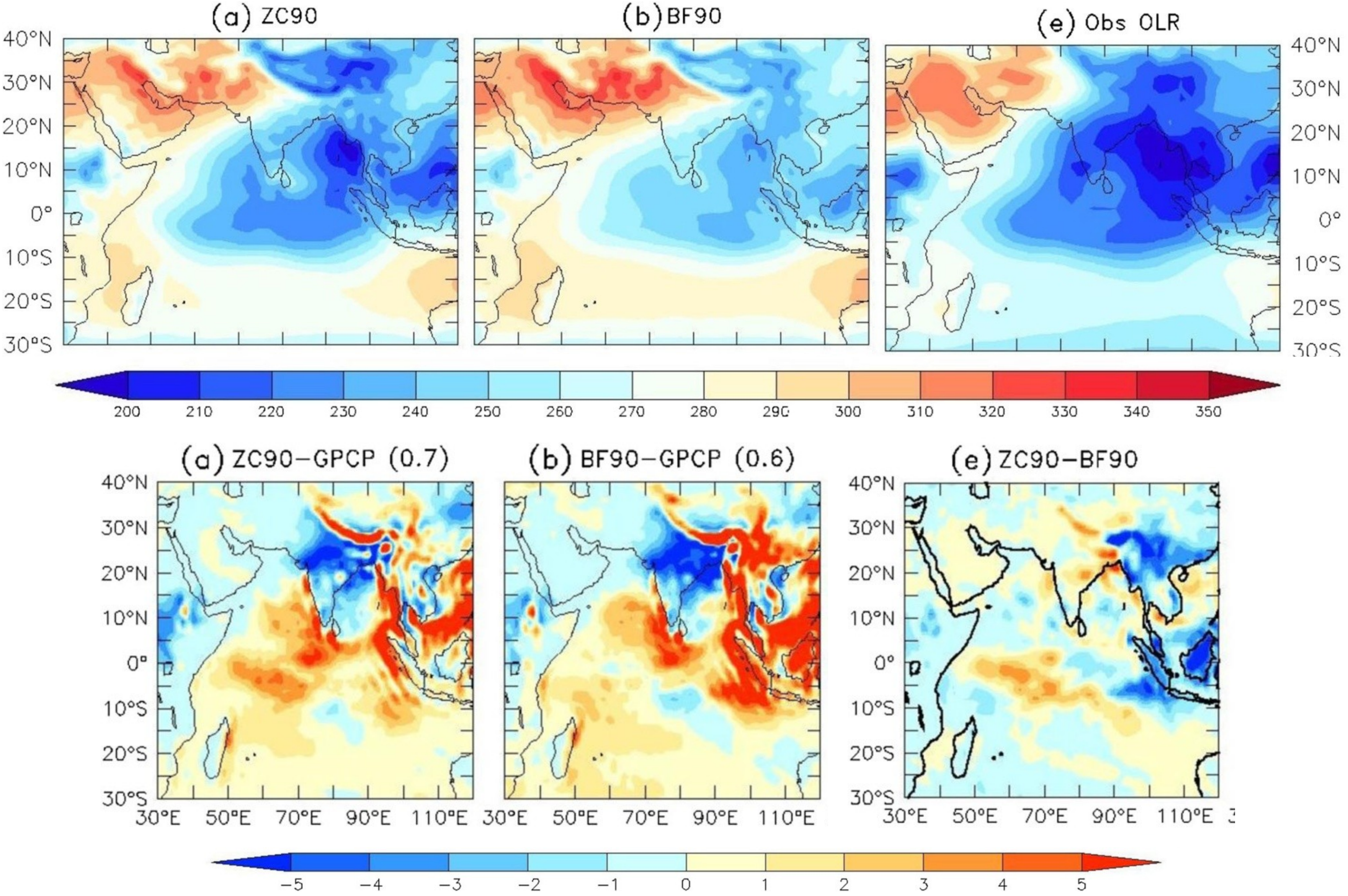


Ice phase in High Cloud - CALIPSO (%)



Hazra et al. (2016),Clim Dyn

Choice of microphysical scheme for the development of Climate Forecast System (CFSv2)



Chaudhari et al., (2015)

Strategy of model development on microphysical processes

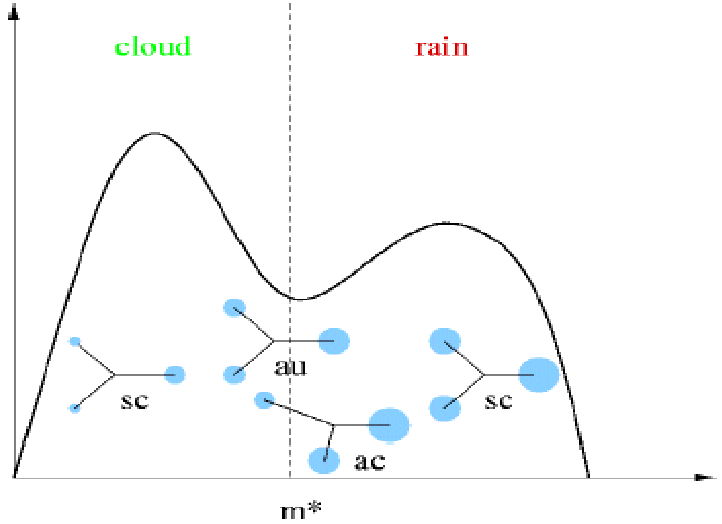
- The improvement in the large-scale organized convection and total precipitation is possible by the increase of stratiform rain fraction in models [*Deng et al.,* 2016; *Aayamohan et al.,* 2016; *Song and Yu* 2004].

- Stratiform rain formation is intimately associated with the formation of cloud condensate, particularly the cloud ice and mixed-phase hydrometeors [*Liu et al.,* 2007; *Kumar et al.,* 2014; *Field and Heymsfield* 2015; *Hazra et al.,* 2017].

Observational guidance

- Guided by observations under the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) [*Kulkarni et al.,* 2012; *Konwar et al.,* 2012; Prabha et al., 2011], a major modification to the existing cloud microphysics scheme in the CFSv2 is undertaken.

Microphysical Tendency



Khain et al. 2015

self collection (sc)
droplet + droplet → droplet

self collection (sc)
rain + rain → rain

autoconversion (au)
droplet + droplet → rain

accretion (ac)
droplet + rain → rain

Microphysical Auto-conversion: cloud water to rain water auto-conversion *Sundqvist et al.,* [1989]:

$$P_{raut} = C_0 q_l \left\{1 - exp\left(-\left(\frac{q_l}{b q_{lcrit}}\right)^2\right)\right\}$$

C_0 :auto-conversion coefficient, q_l : the clw and q_{lcrit} : critical clw. b : cloud cover . q_{lcrit} (***Rotstayn* 2000):**

$$q_{lcrit} = \frac{4}{3}\pi r_{crit}^3 N_c \rho_l / \rho_a$$

Convective Auto-conversion: The precipitation formation from convective parameterization.

autoconversion function need to be modified as vary based on resolution (Wu et al., 2010).

Modified production term

Newly incorporated production term

$$P = P_{raut} + P_{saci} + P_{saut} + P_{racw} + P_{sacw}$$

$$P_{racw} = E_{cr}.q_c.P_{rprc} \qquad P_{sacw} = E_{cr}.q_c.P_{sprc}$$

Results of ISM climate simulation using our physically based modified convective microphysics (MCM) scheme in CFSv2

AGU PUBLICATIONS

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1002/2017MS000966

Progress Towards Achieving the Challenge of Indian Summer Monsoon Climate Simulation in a Coupled Ocean-Atmosphere Model

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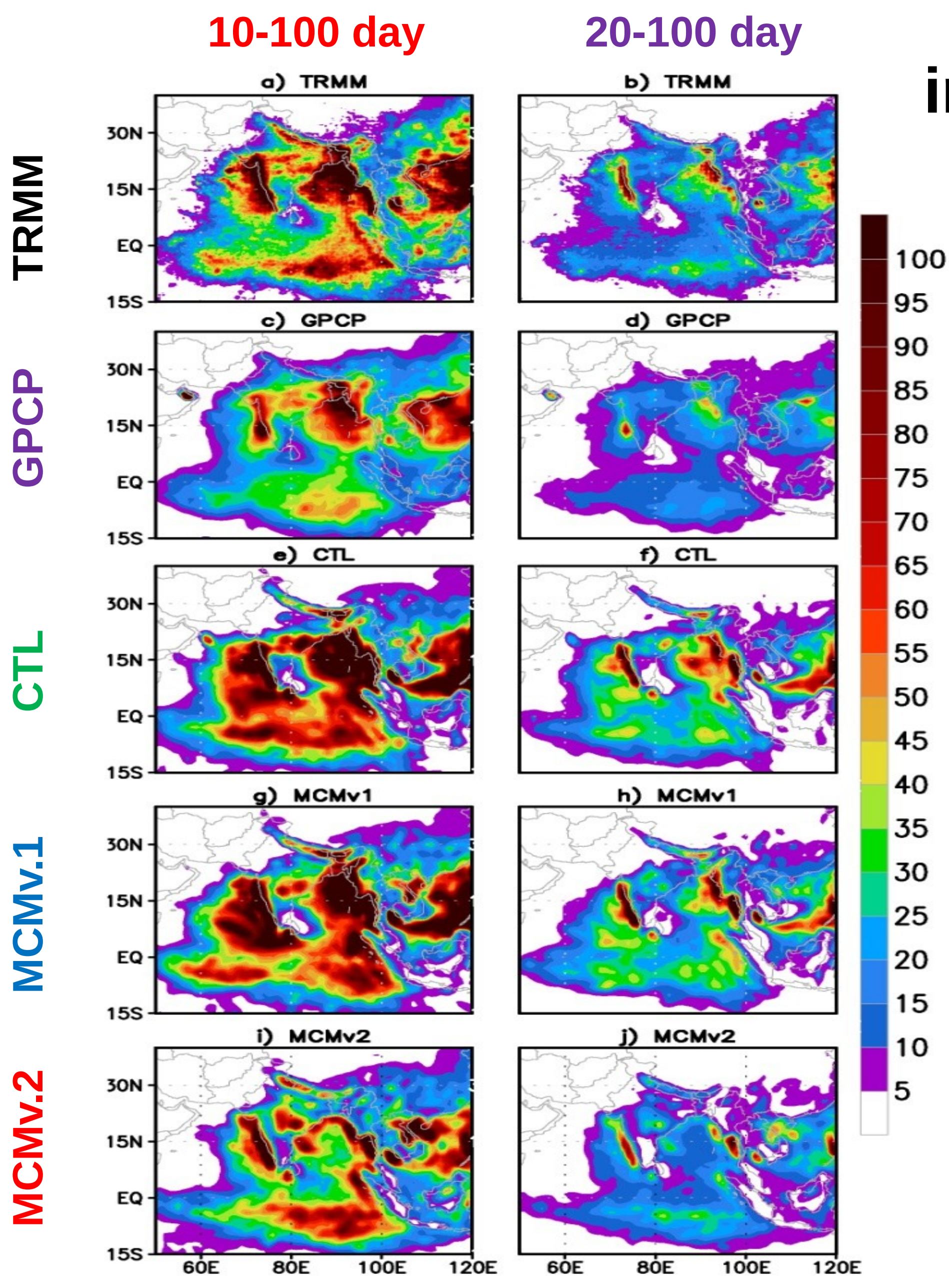
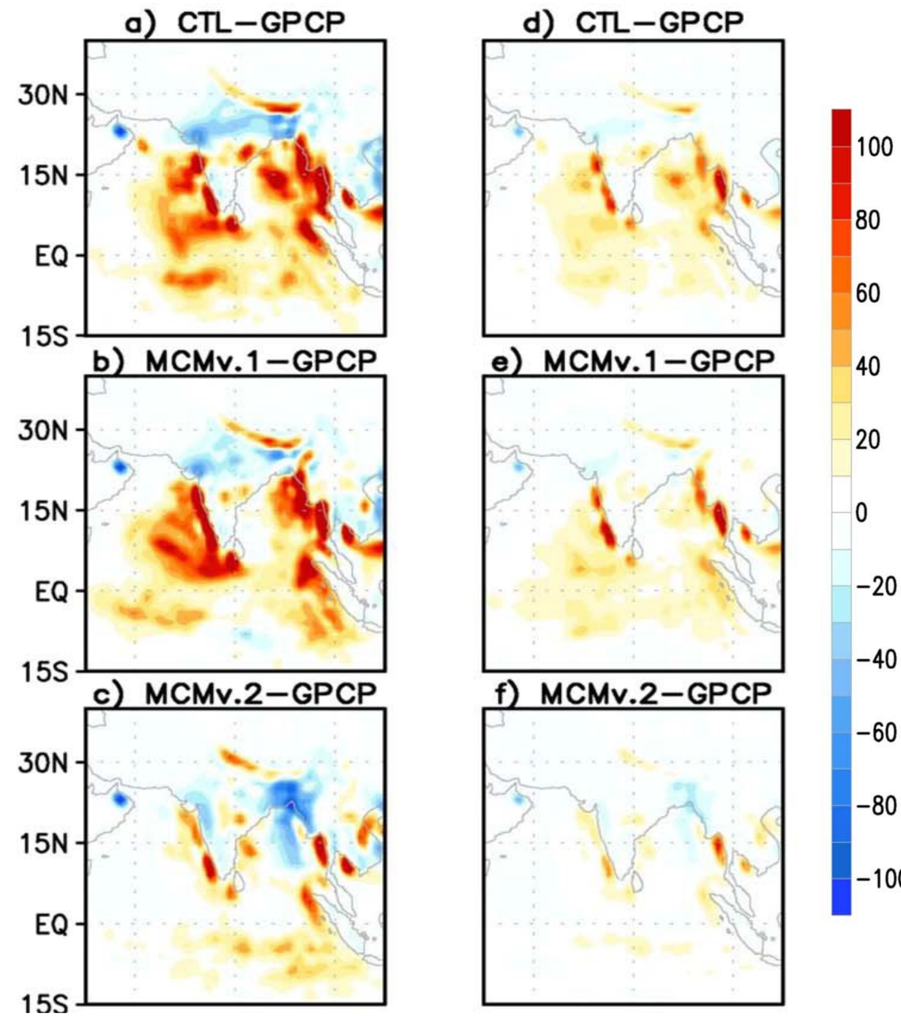
[1]Indian Institute of Tropical Meteorology, Pashan, Pune, India, [2]Cotton College State University, Guwahati, India

Key Points:
- A physically based modified convective microphysics scheme is implemented in the NCEP CFSv2
- The convective microphysics is found to be important for simulating the observed monsoon intraseasonal oscillations (MISOs)

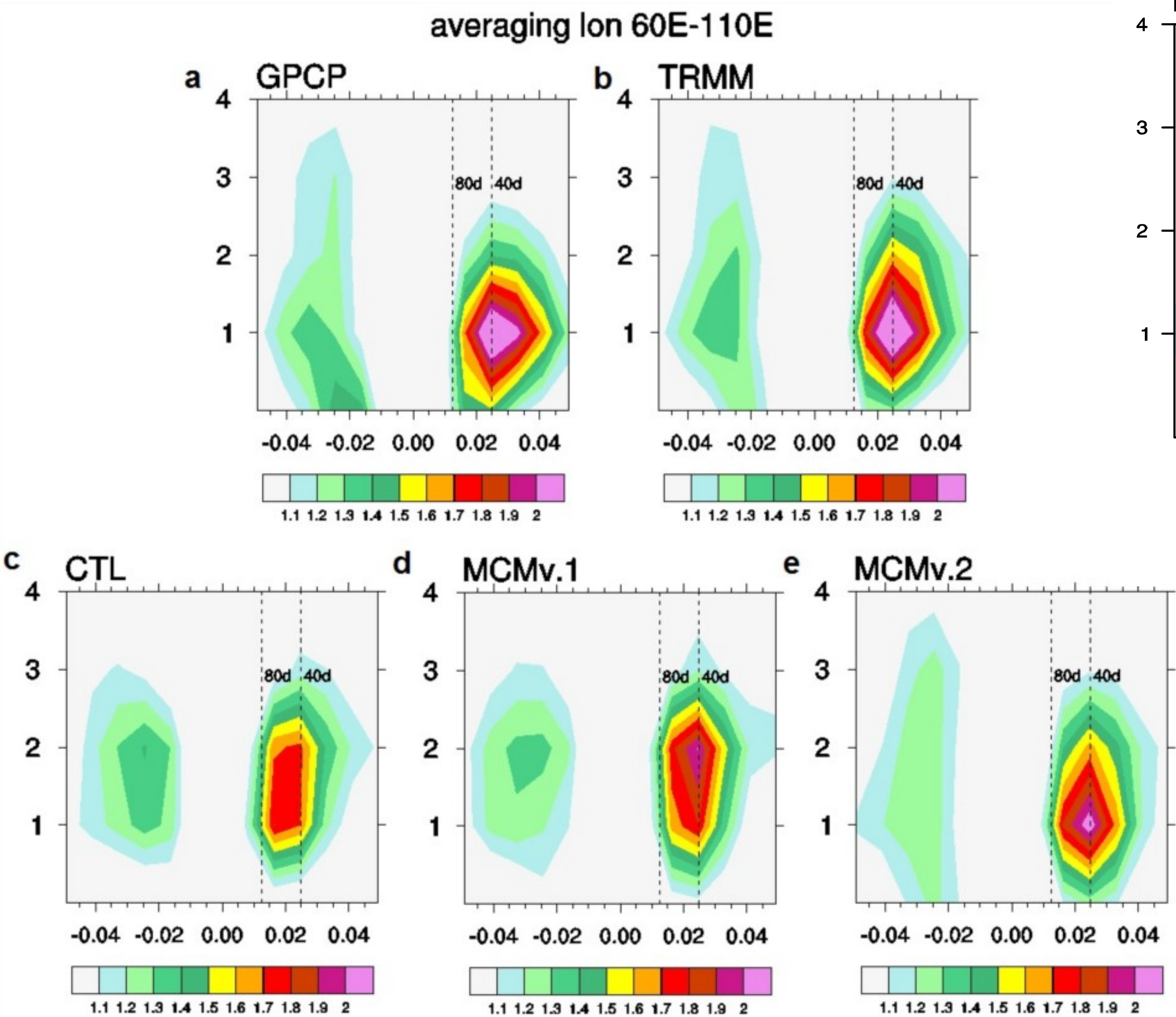
Improvement of total intraseasonal variance (ISV)

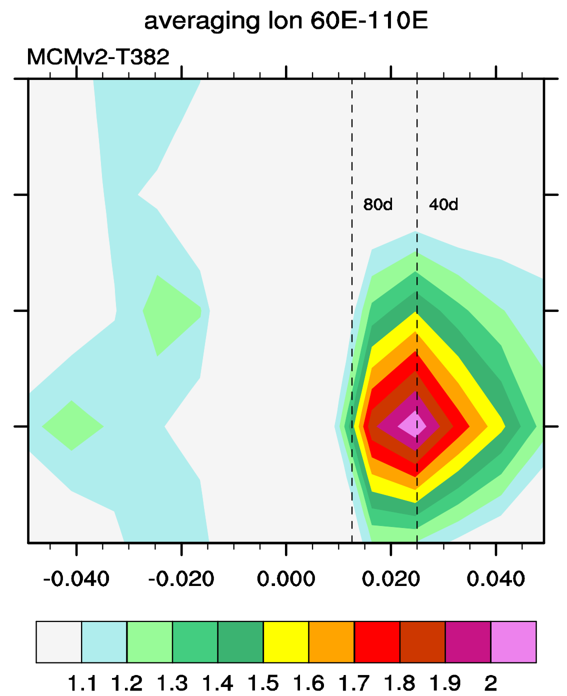




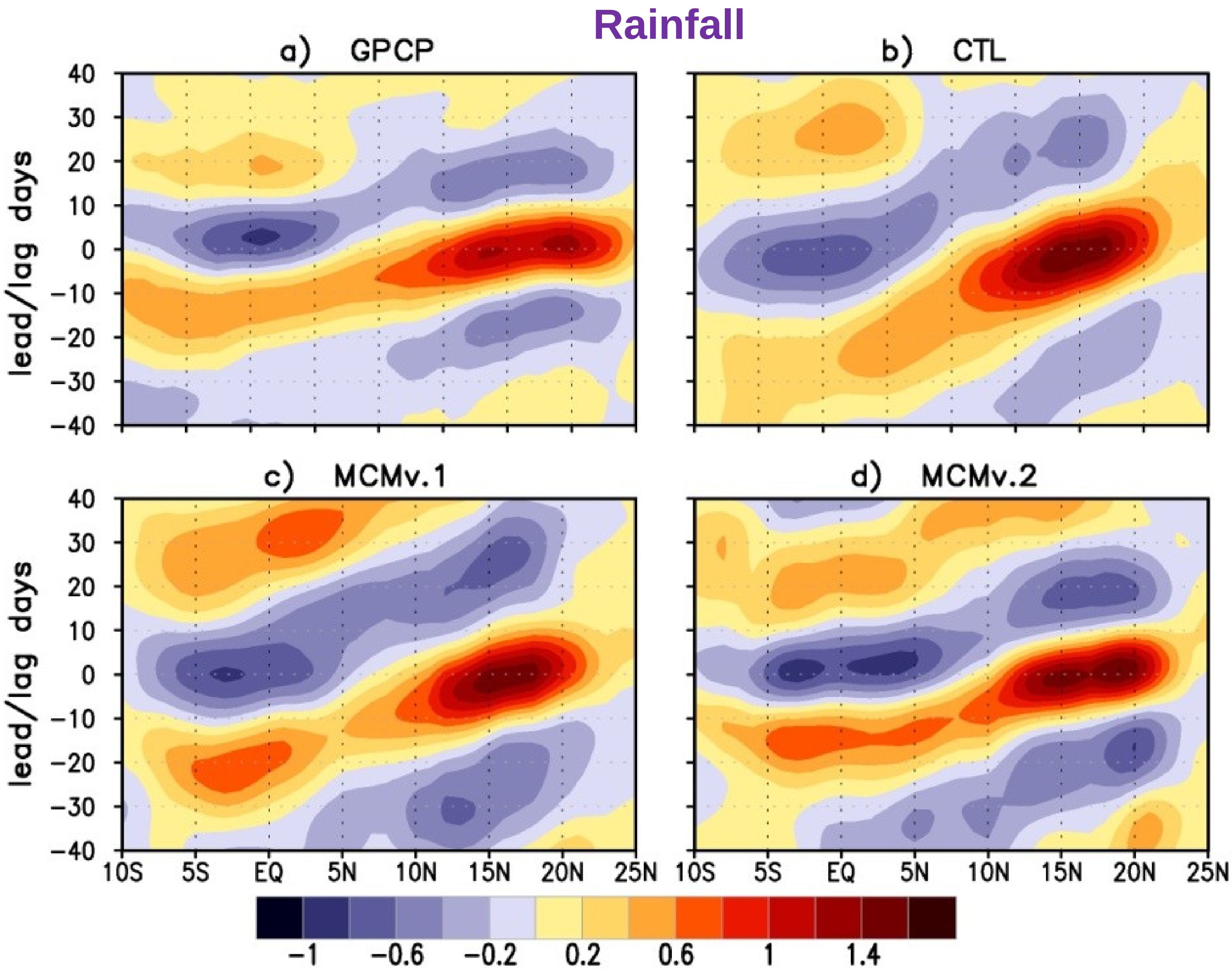
Hazra et al., (2017), JAMES

Improvement of Space-time spectra of the low frequency 30-60 day mode



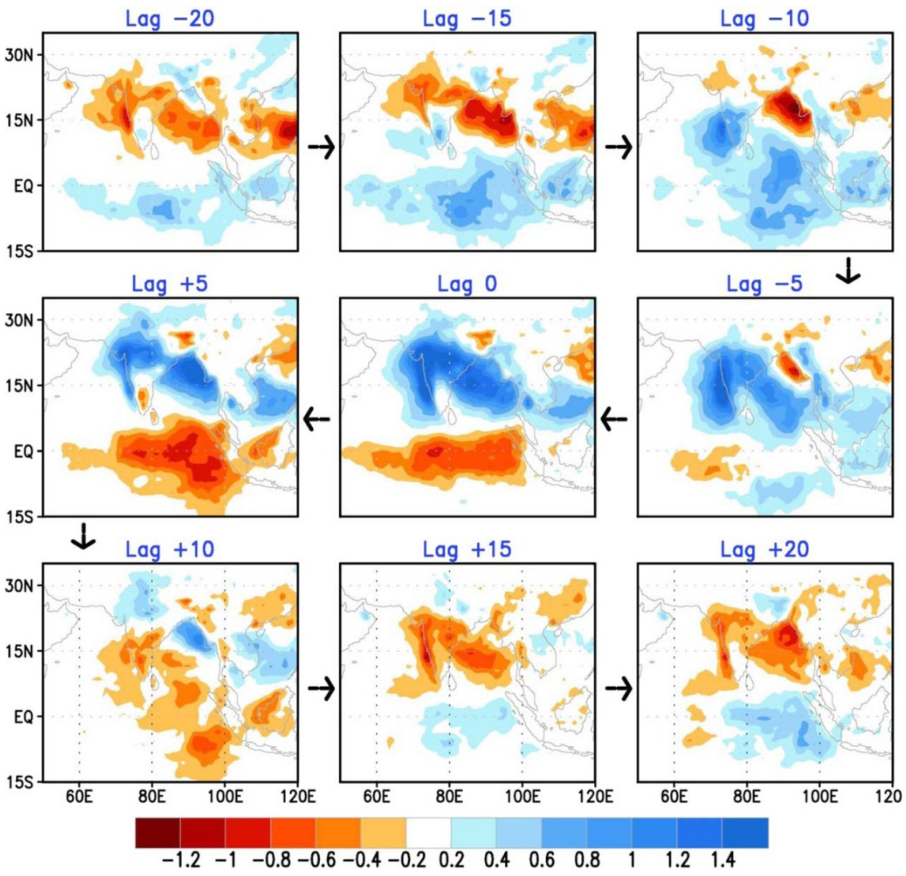


Improvement the speed of northward propagation of ISOs

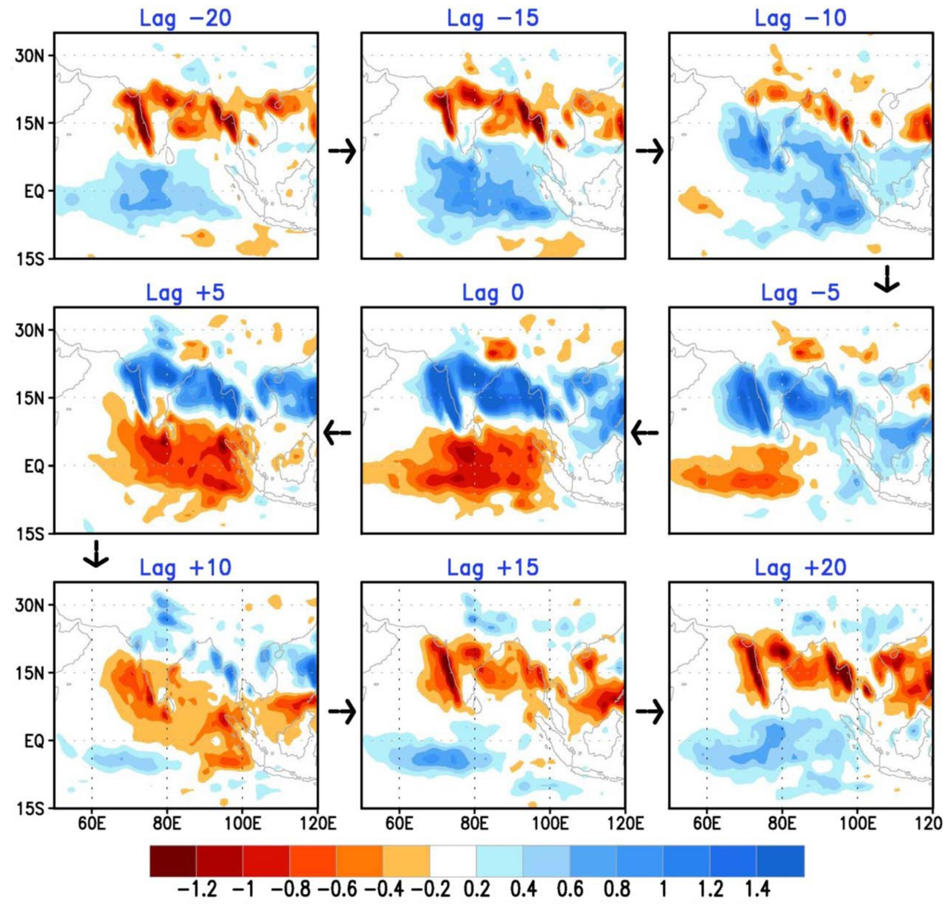


Improvement in space-time evolution and northward propagation of the south-east to north-west tilted ITCZ (in terms of phase and amplitudes)

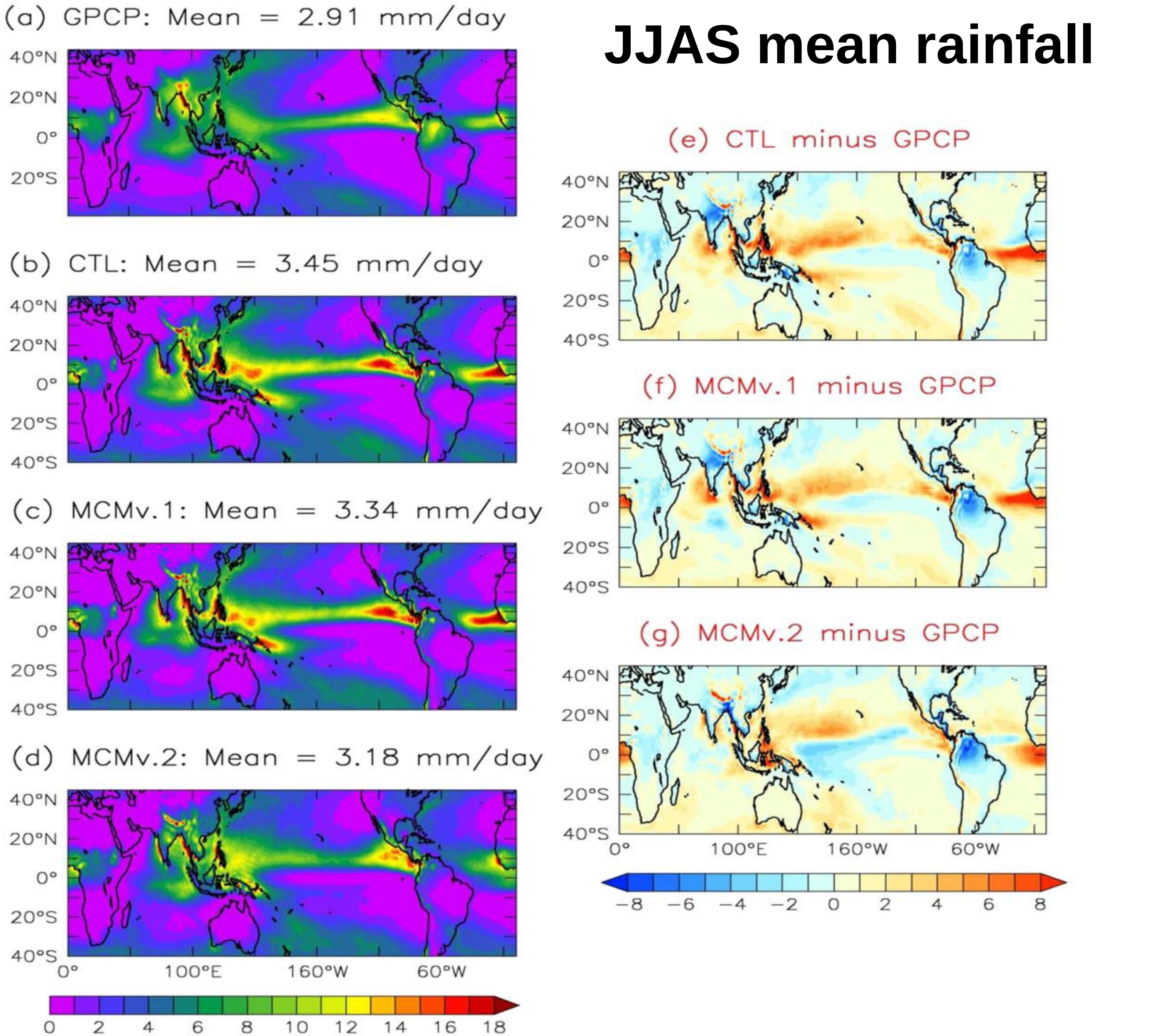
GPCP



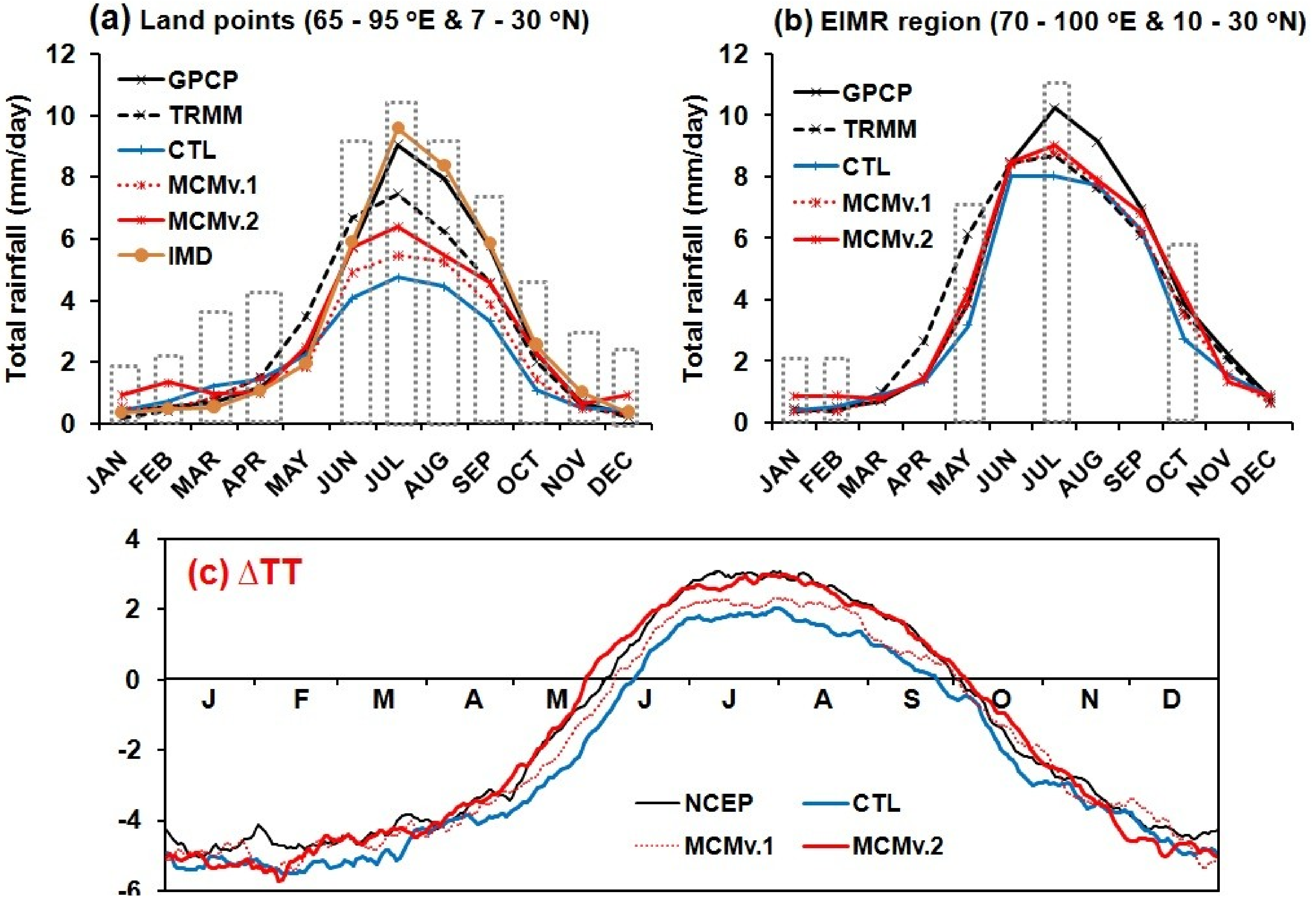
CTL MCMv2



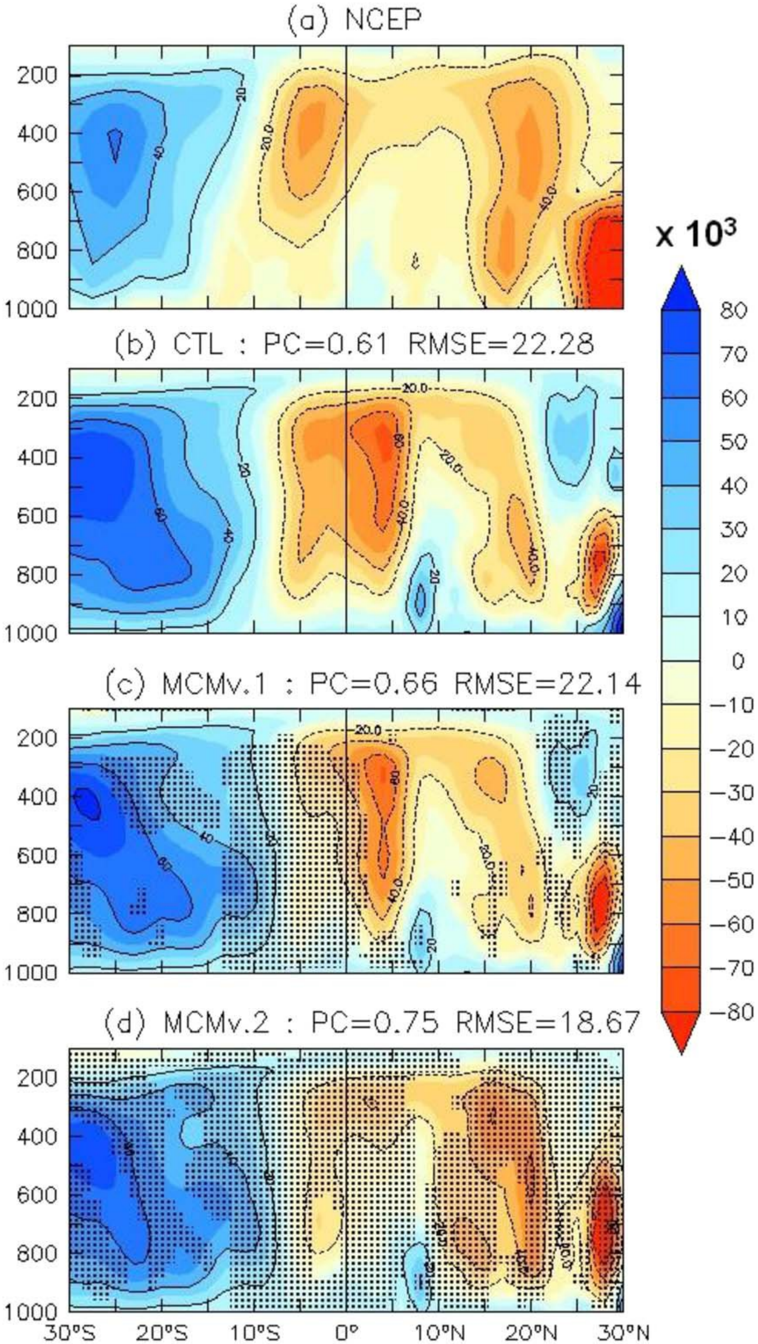
JJAS mean rainfall



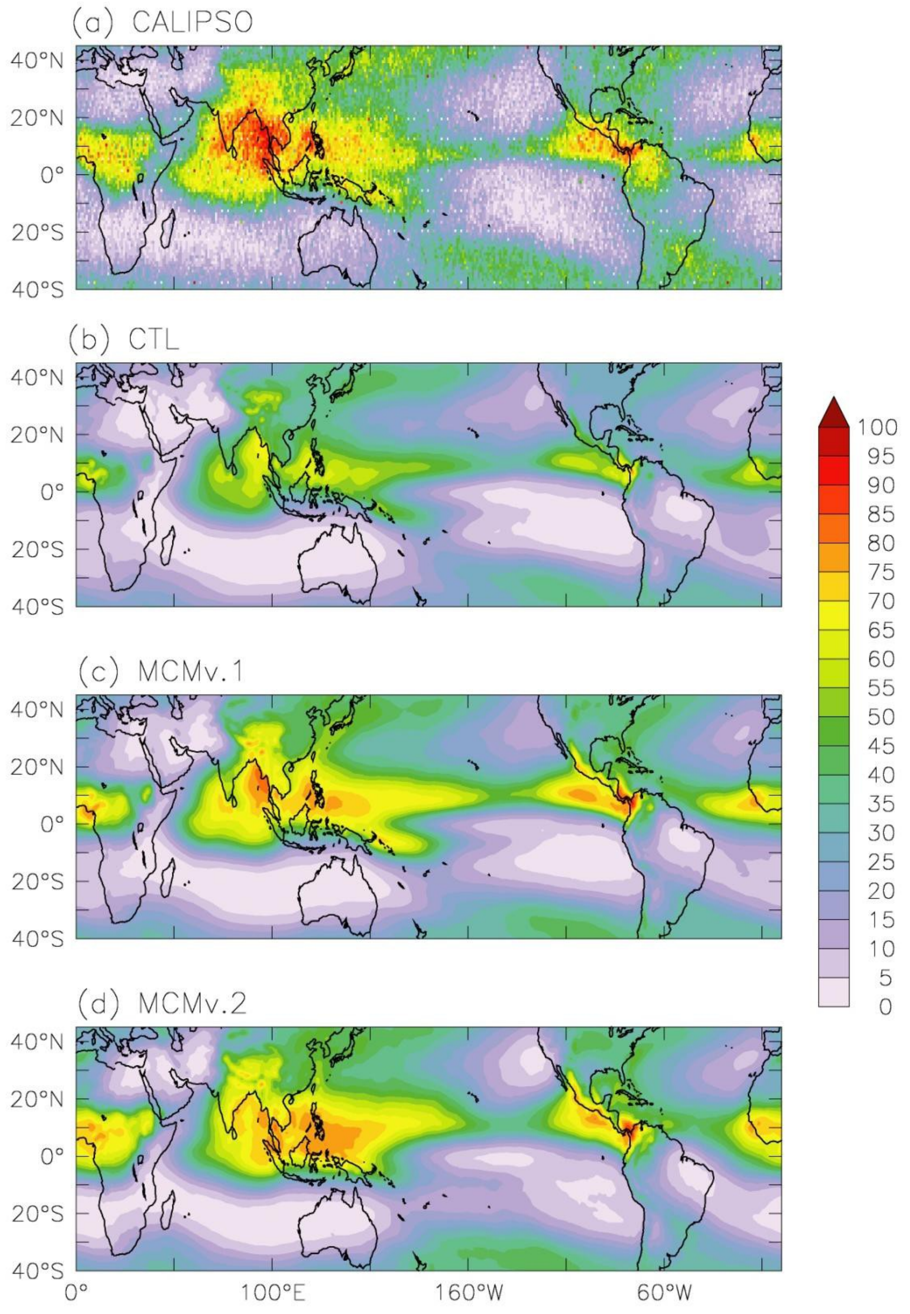
Annual cycle of rainfall and Tropospheric Temperature gradient

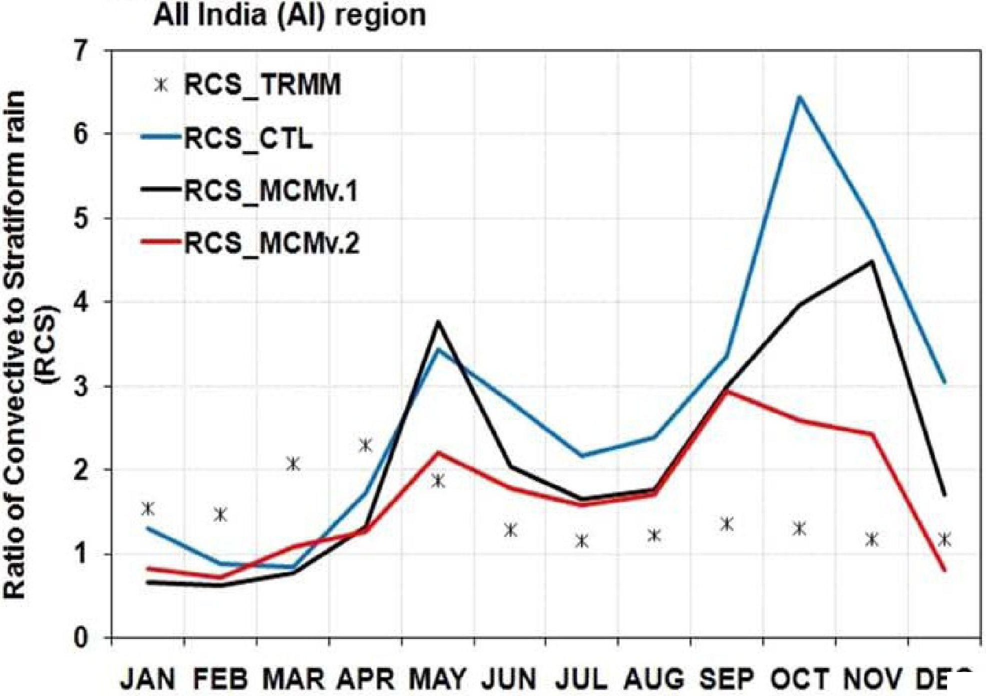


Hadley circulation



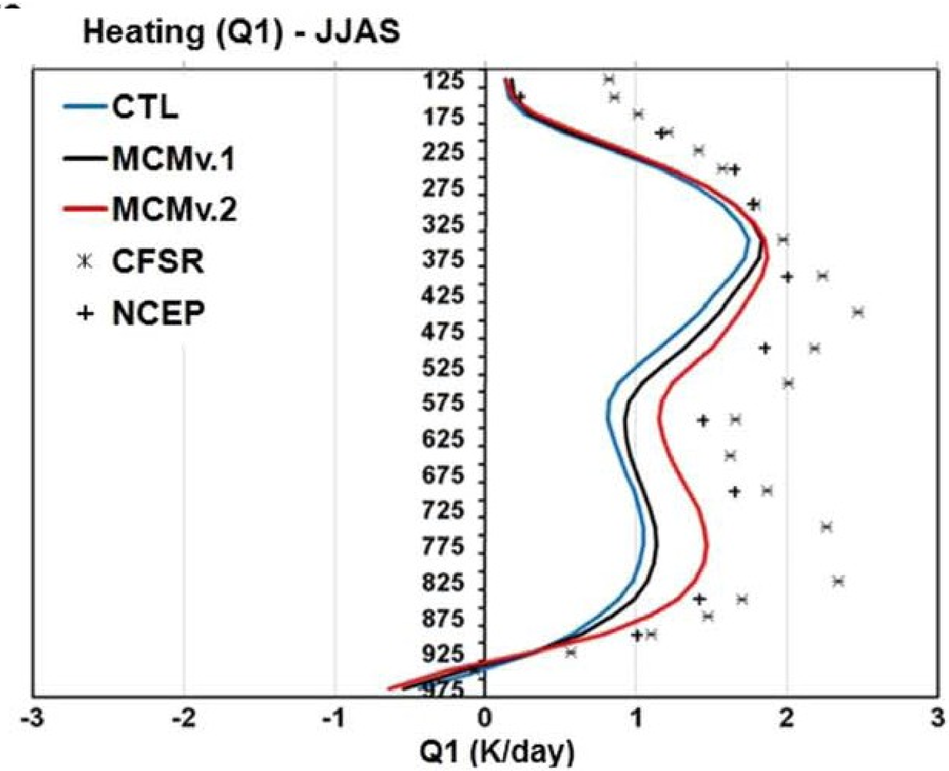
High Cloud Fraction (%)





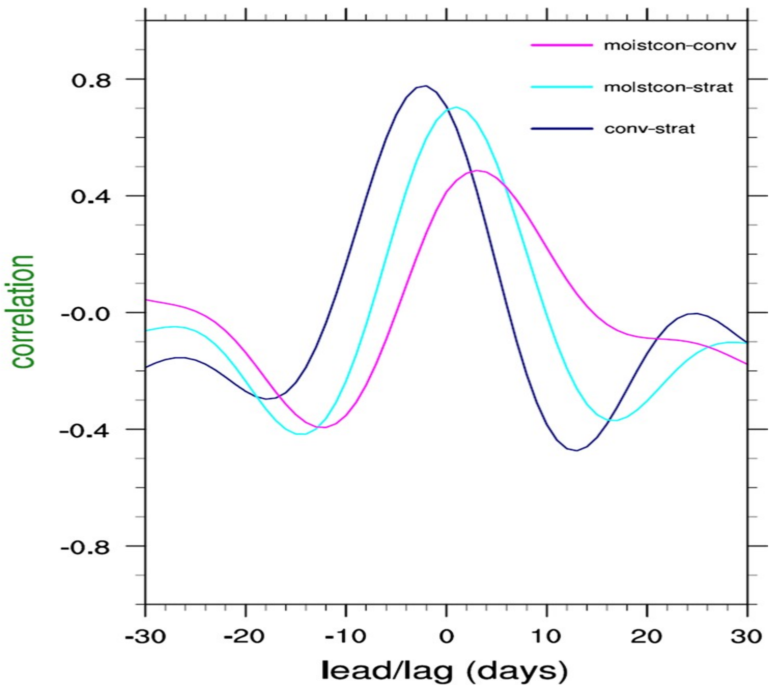
Ratio of convective to stratiform rain (RCS)

Calculation of apparent heat source (Q1)

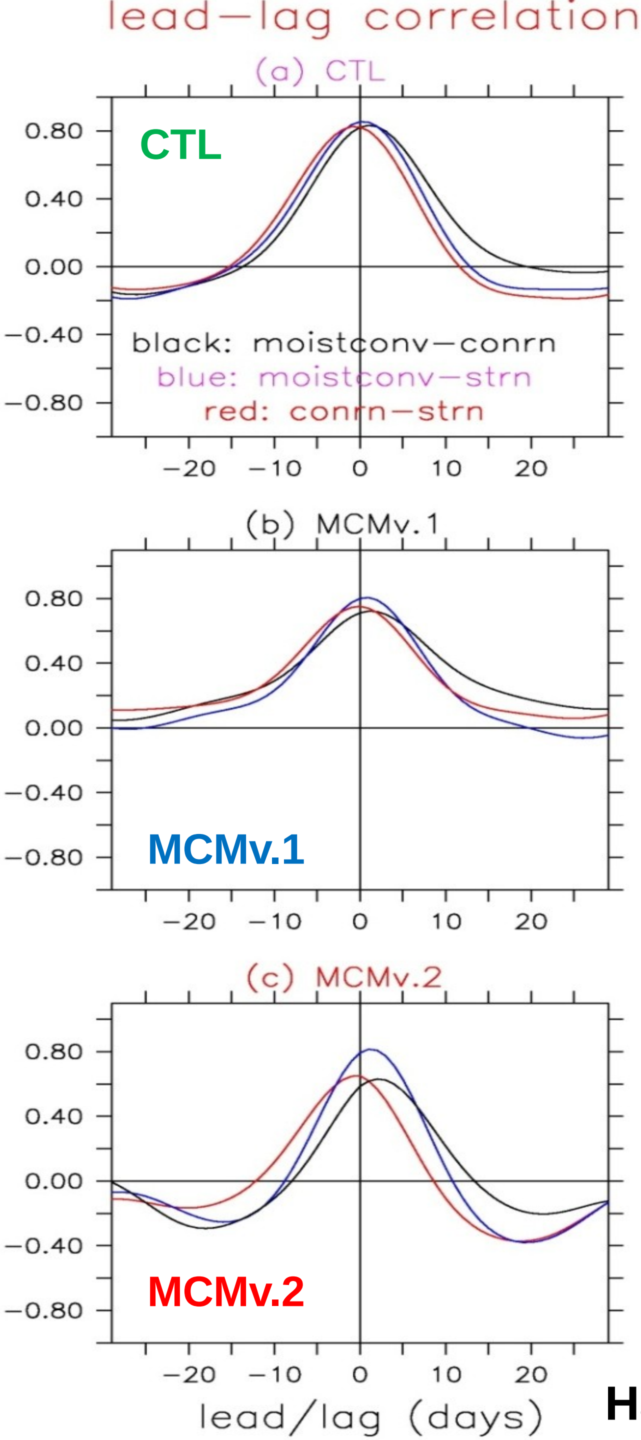


Observation

Lead–lag correlation between convective rain and stratiform

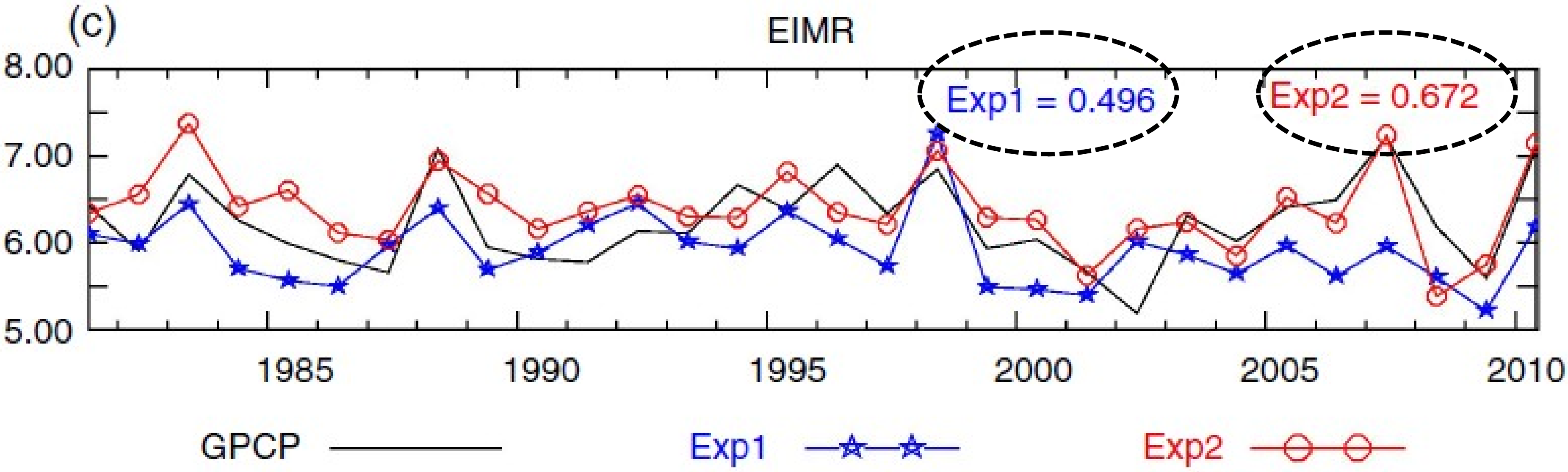


S. Kumar et al., (2017)



Hazra et al., (2017)

Conclusions



stratiform rain fraction) are consistently improved.

IAV of rainfall based indices using observation (solid line) and both Exp1 (line with star) and Exp2 (line with open circle) for (c) EIMR (65–95E, 5–35 N). (Pokhrel et al. 2018)

❖ **High fidelity in the simulation of MISOs in association with improved stratiform rain fraction leads to the improved seasonal mean ISMR.**

This development may lead to improve ISMR skill.

Future

Need 2-moment microphysical parameterization to account aerosol effect in Global climate model.

Ice Nuclei

Classical nucleation theory based heterogeneous ice nucleation parameterization

(Chen-Hazra-Levin, 2008; Hoose-Kristjansson-Chen-Hazra 2010)

Spectrometer for Ice Nuclei

Cloud Condensation Nuclei

Interaction between aerosol (CCN), dynamics and cloud microphysics on transition of MISO

(Hazra-Goswami-Chen, 2013)

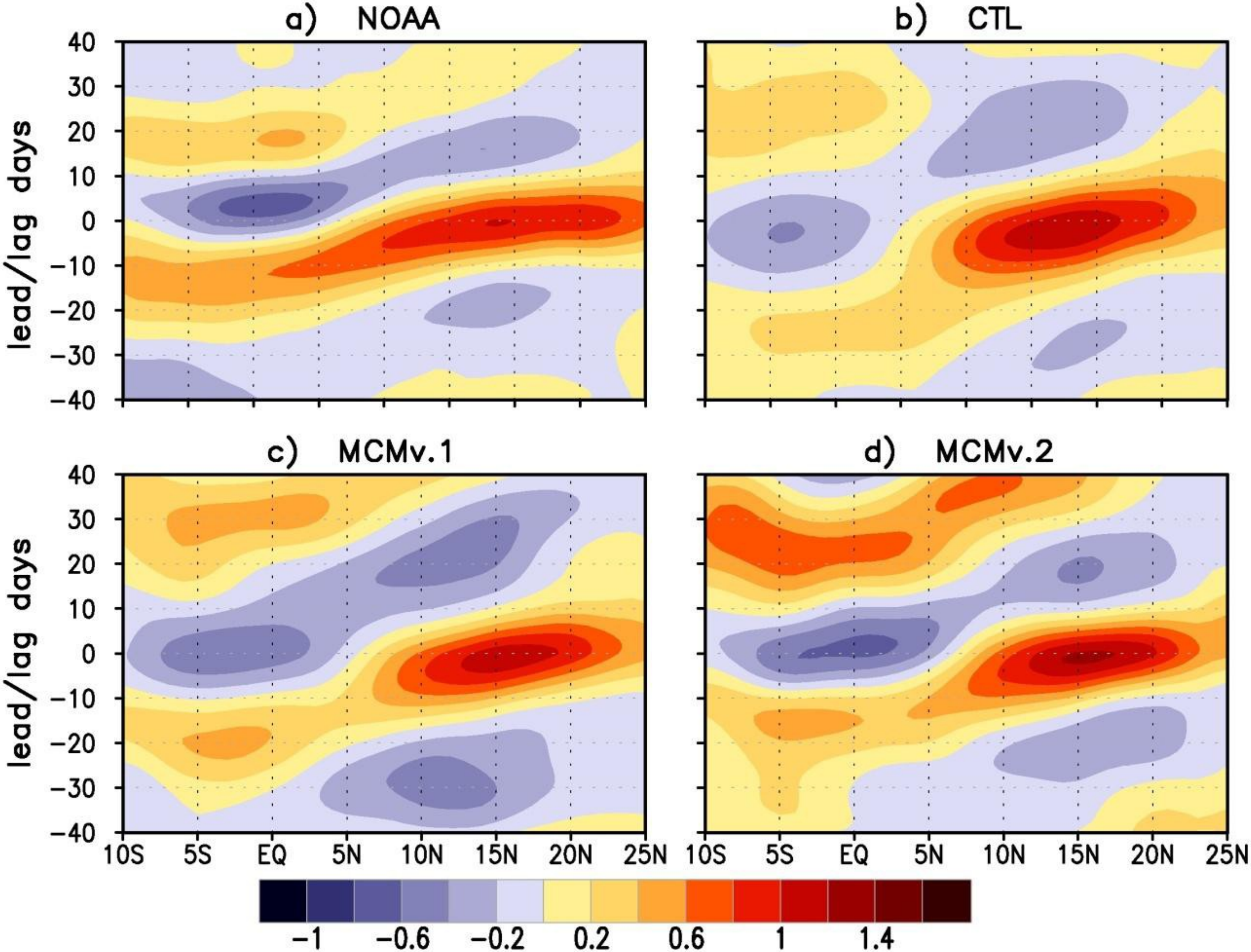
CCN Counter

nk you for the kind attentio

Questions ???

Backup ……..

Outgoing Long-wave radiation (OLR)



Cold-cloud microphysics or Ice-phase microphysics

Nucleation

Empirical ice nucleation

$$N_i = a \cdot \exp(b \cdot T_{sup})$$

Fletcher 1962

$$N_i = [(S_i - 1)/(S_0 - 1)]^b$$

Huffman 1973

$$N_i = a.\exp(b.T_{sup}).[(S_i - 1)/(S_0 - 1)]^b$$

Cotton 1986; Mayers 1992

$$N_i = a(273.16 - T)^b (N_0)^{(c.(273.16 - T)+d)}$$

DeMott et al. 2010

Classical nucleation theory: deposition nucleation & immersion freezing

The surface nucleation rate J_s describes the rate of formation

→ **it scales with time (s^{-1}) and particle surface area (m^{-2})!**

$$J = 4\pi r_N^2 J_s = 4\pi r_N^2 A_1 n^* Z$$

Where J_s is the surface nucleation rate with:

A_1 = rate of collisions **to overcome nucleation barrier**

n^* = number of critical clusters **(per unit surface area)**

Z = Zeldovich factor

$$n^* = n_1 \cdot \exp\left(-\frac{\Delta g_g}{kT}\right) \qquad Z = \frac{1}{n_g} \cdot \sqrt{\frac{\Delta g_g}{3\pi kT}} \qquad n_g = \frac{4 r_g^3}{3 \upsilon_w}$$

$$J = 4\pi r_N^2 \, A_1 \, n_1 \cdot \exp\left(-\frac{\Delta g_g}{kT}\right) \frac{1}{\frac{4 r_g^3}{3\upsilon_w}} \cdot \sqrt{\frac{\Delta g_g}{3\pi kT}}$$

This form of the classical nucleation theory is valid for both immersion freezing and deposition nucleation!

Chen-Hazra-Levin (2008), ACP; Hoose, Kristjansson, Chen, Hazra (2010), JAS

Classical nucleation theory: deposition nucleation & immersion freezing

$$J = 4\pi r_N^2 \, A_1 n_1 \cdot \exp\left(-\frac{\Delta g_g}{kT}\right) \frac{1}{\frac{4 r_g^3}{3 \upsilon_w}} \cdot \sqrt{\frac{\Delta g_g}{3\pi kT}}$$

In this formula, the following parameters are specific to the mode of ice formation:

Deposition Nucleation

$$A_1 = 4\pi r_g^2 \cdot \frac{e}{\sqrt{2\pi m_w kT}}$$

$$r_g = \frac{2\upsilon_w \sigma_{i/v}}{\Delta g_b} \qquad \Delta g_b = kT \ln S_i$$

$$n_1 = \frac{e}{\nu_s \sqrt{2\pi m_w kT}} \cdot \exp\left(\frac{-\Delta g_d}{kT}\right)$$

$$\Delta g_g = \Delta g_g^{\circ} \cdot f = \frac{4\pi}{3} \sigma_{i/v} r_g^2 f = \frac{16\pi \upsilon_w^2 \sigma_{i/v}^3}{3\Delta g_b^2} \cdot f$$

Immersion Freezing

$$A_1 = \frac{kT}{h} \cdot \exp\left(\frac{-\Delta g_a}{kT}\right)$$

$$r_g = \frac{2\upsilon_w \sigma_{i/w}}{\Delta g_b} \qquad \Delta g_b = KT \ln \frac{e_{sw}}{e_{si}}$$

$$n_1 = 1.0 \cdot 10^{19} \text{ m}^{-2}$$

$$\Delta g_g = \Delta g_g^{\circ} \cdot f = \frac{4\pi}{3} \sigma_{i/w} r_g^2 f = \frac{16\pi \upsilon_w^2 \sigma_{i/w}^3}{3\Delta g_b^2} \cdot f$$

Classical nucleation theory: deposition nucleation & immersion freezing

Deposition Nucleation

$$\Delta g_g = \Delta g_g^{\circ} \cdot f = \frac{4\pi}{3} \cdot \sigma_{i/v} \cdot r_g^2 \cdot f$$
$$= \frac{16\pi \upsilon_w^2 \sigma_{i/v}^3}{3\,\Delta g_b^2} \cdot f$$

Immersion Freezing

$$\Delta g_g = \Delta g_g^{\circ} \cdot f = \frac{4\pi}{3} \cdot \sigma_{i/w} \cdot r_g^2 \cdot f$$
$$= \frac{16\pi \upsilon_w^2 \sigma_{i/w}^3}{3\,\Delta g_b^2} \cdot f$$

The Gibbs free energy of ice germ formation Δg_g is similar to the one for homogeneous nucleation Δg_g° except for the compatibility parameter *f*. For flat surfaces, the compatibility parameter *f* is

$$f(m) = \frac{(2+m)(1-m)^2}{4} \quad \text{with} \quad m = \cos\theta$$

The contact angle θ is different for the two nucleation modes and describes how the particle properties (chemistry) influence heterogeneous nucleation:

$$\cos\theta_{dep} = \frac{\sigma_{air/IN} - \sigma_{ice/IN}}{\sigma_{air/ice}}$$

$$\cos\theta_{imm} = \frac{\sigma_{water/IN} - \sigma_{ice/IN}}{\sigma_{water/ice}}$$

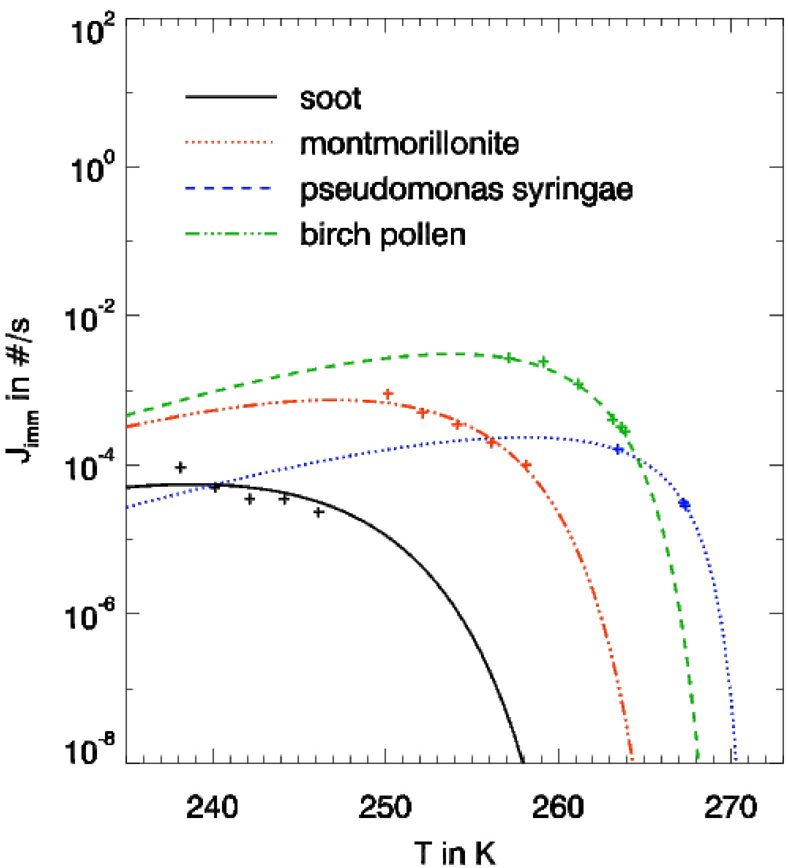
Nucleation thermodynamic parameters determined from laboratory data

$$J = A' \cdot r_N^2 \cdot \sqrt{f} \cdot \exp\left(\frac{-\Delta g^{\#} - \Delta g_g \cdot f}{kT} \right)$$

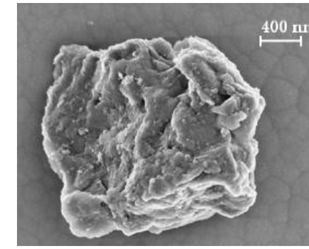
A' & Δg_g are ambient parameter

Properties of IN:

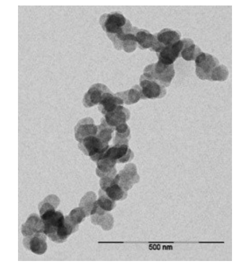
1. **Particle radius**
2. **Activation energy**
3. **Wetting coefficient or contact angle**



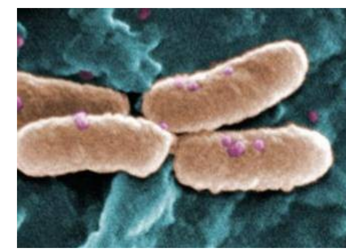
species \ parameter	θ	$\Delta g^{\#}$
soot	33.2	13.8
E. herbicola	16.0	12.7
P. syringae	12.5	12.8
P. aeruginosa	5.30	12.2
Grass	18.4	15.5
Oak	20.6	15.1
Pine	17.8	13.2
Birch	18.8	15.0
Eucalyptus	18.4	15.7
China rose	20.3	15.8
Hematite (0.03)	69.4	9.90
Hematite (0.13)	63.4	14.3
Asian dust	15.2	1.17
Saharan dust	14.7	1.31
Arizona test dust	7.85	2.32



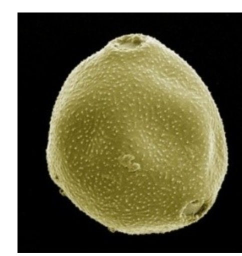
Montmorillonite (Welti et al , 2009)



Soot (M. Jargelius)



Pseudomonas aeruginosa (J. H. Carr)



Birch pollen (J. Derksen)

Chen-Hazra-Levin (2008), ACP; Hoose, Kristjansson, Chen, Hazra (2010), JAS