An attempt to simulate Mean state in the NCEP Climate Forecast System (Version 2) through a Stochastic Multicloud Model calibrated through Indian Radar Data

By

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Introduction

- With the ongoing threat of climate change, and the increasing importance of climate science in public sectors, the development of accurate and reliable climate models is crucial. A typical climate model, or General Circulation Model (GCM) functions at a large scale and discretizes the atmosphere by dividing it into a grid, where each grid square is on the order of 10 to 100km.

- One issue is that there are many processes that occur at the subgrid scale and will not be resolved, however will still significantly affect the climate. The solution is to develop models to parametrize these small scale processes so that they may be taken into account in the larger scale GCM.

- One such unresolved process is cumulus convection. It occurs at a small scale however the formation and dissipation of these clouds significantly affects atmospheric dynamics.

- A stochastic model has been previously developed by Khouider et al. 2010 to parametrize cumulus convection.

- The stochastic Multi Cloud Model (SMCM) considers cumulus convection on a single grid square of a GCM.

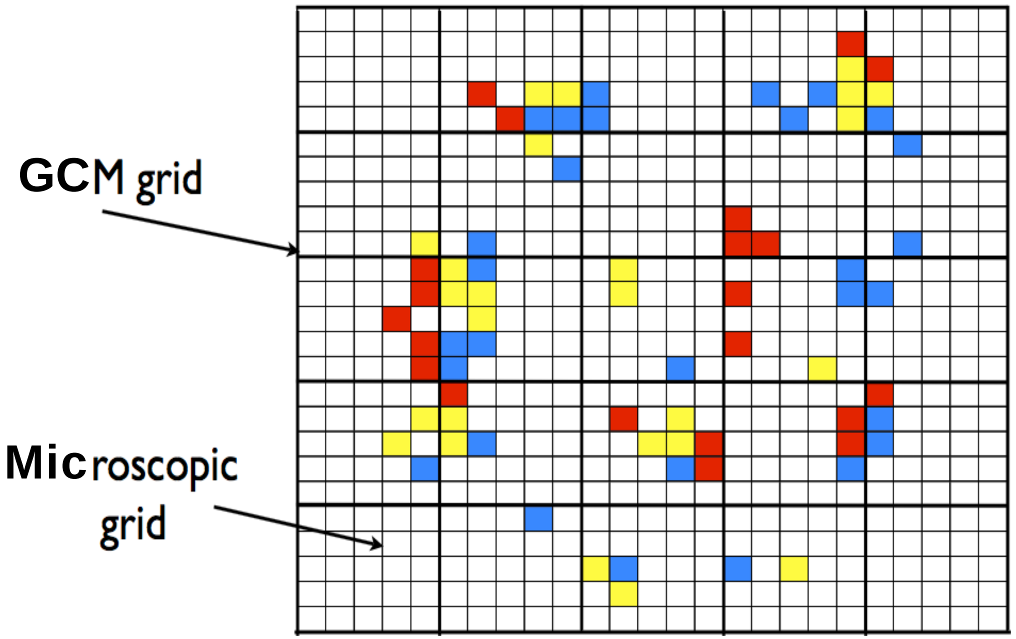
- It divides the grid square into a lattice, where each lattice cell may contain a single type of cloud, either cumulus congestus, deep, stratiform, or clear sky, and the SMCM models the transitions between these different states.

- The model considers three types of clouds, each of which provide heating or cooling to the atmosphere in order to alter the large-scale climate variables.

- Cumulus congestus clouds tend to form first and heat the lower troposphere and cool the upper troposphere.

- Deep clouds may form directly from clear sky or from congestus clouds and are towering clouds that provide rainfall and heat the entire troposphere.

- Stratiform clouds may follow deep clouds and they heat the upper troposphere while cooling the lower troposphere.



Each lattice is either occupied by a cloud of certain type or is clear sky…time varying!

- The heating, cooling and precipitation provided by the clouds directly affect the large-scale thermodynamic variables. And the transition probabilities between the different states are calculated by transition rates that are based on large-scale dynamic and thermodynamic variables.

- The large-scale variables used are the convective available potential energy (CAPE) summed up over the whole troposphere (C), the lower troposphere integrated CAPE (CL) and the mid troposphere dryness (D).

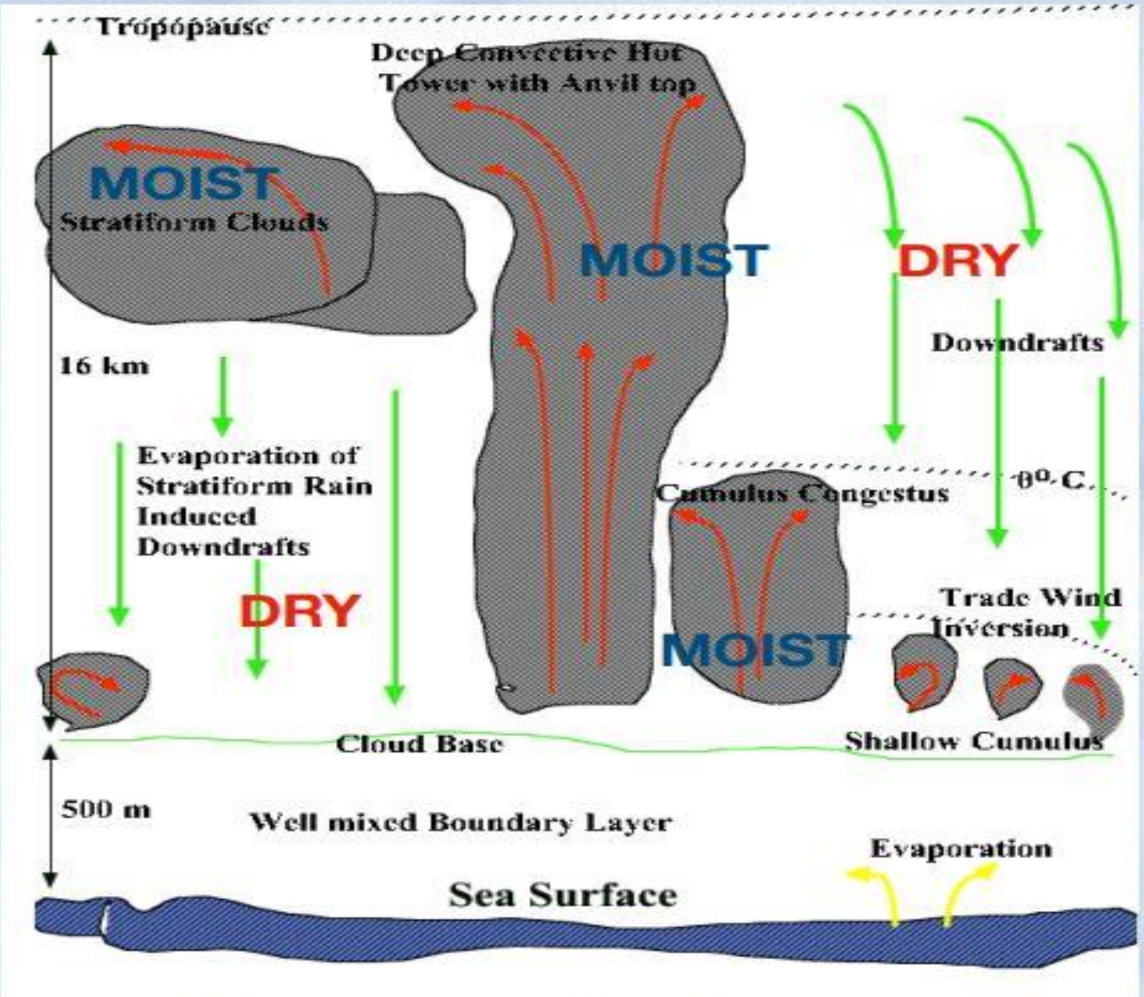
- Further, A Bayesian inference model was developed as a method to infer timescale parameter values from real or simulated data (De la Chevrotiere et al. 2014).

$$
\begin{aligned}
r_{01} &= \frac{1}{\tau_{01}}\Gamma(C_L)\Gamma(D) \\
r_{10} &= \frac{1}{\tau_{10}}\Gamma(D) \\
r_{12} &= \frac{1}{\tau_{12}}\Gamma(C)(1-\Gamma(D)) \\
r_{02} &= \frac{1}{\tau_{02}}\Gamma(C)(1-\Gamma(D)) \\
r_{23} &= \frac{1}{\tau_{23}} \\
r_{20} &= \frac{1}{\tau_{20}}(1-\Gamma(C)) \\
r_{30} &= \frac{1}{\tau_{30}}
\end{aligned}
$$

$$\Gamma(x) = \{1 - e^{-x} \text{ if } x > 0, 0 \text{ otherwise } \}$$

where rij is the transition rate from state i to state j and the states 0,1,2 and 3 represent clear sky, congestus cloud, deep, and stratiform cloud, respectively. The rates also rely on a series of timescale parameters, τij , one for each transition. The large-scale variables are observable from data, and the timescale values are not observable so are assumed values or must be inferred from data.

Multicloud—building block model



Khouider and Majda (2006)

- Not based on a column model
- Based on observed features of tropical convective systems
- Convection is integrated in equations of motion: direct feedback
- Convection responds to progressive adjustment of environmental variables
- Allows interactions across scales -- between moisture and precipitation
- Successful in representing CCWs and Tropical Intra-seasonal oscillations in both simple models and in aquaplanet HOMME GCM (MJO and monsoon variability)

Implementation of the Four-cloud Model:

- The 3 cloud SMCM was expanded and developed into a four-cloud model.

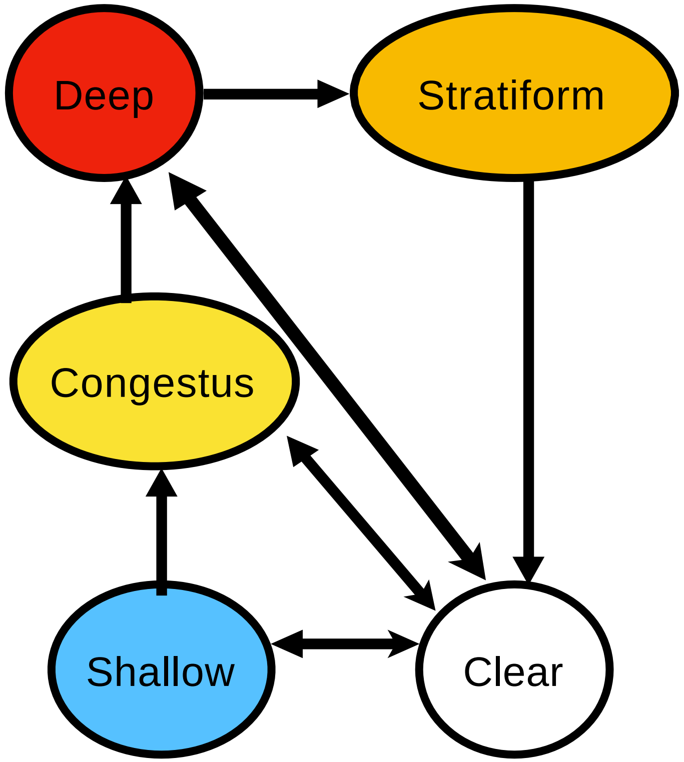
- In addition to cumulus congestus, deep and stratiform, a fourth cloud type, shallow cumulus, was added to the model. Shallow cumulus clouds tend to have a high area fraction so the addition of this cloud makes the model much more realistic.

- This involves updating the formulas for the transition rates. Two additional large-scale variables are added namely the convective Inhibition (CN), and the environmental vertical velocity (W) along with other large-scale variables such as the convective available potential energy (CAPE) summed up over the whole troposphere (C), the lower troposphere integrated CAPE (CL) and the mid tropospheric dryness (D). The rate formulas are also updated depending on these new variables.

4 cloud-type SMCM: Intuitive Probability Rules:

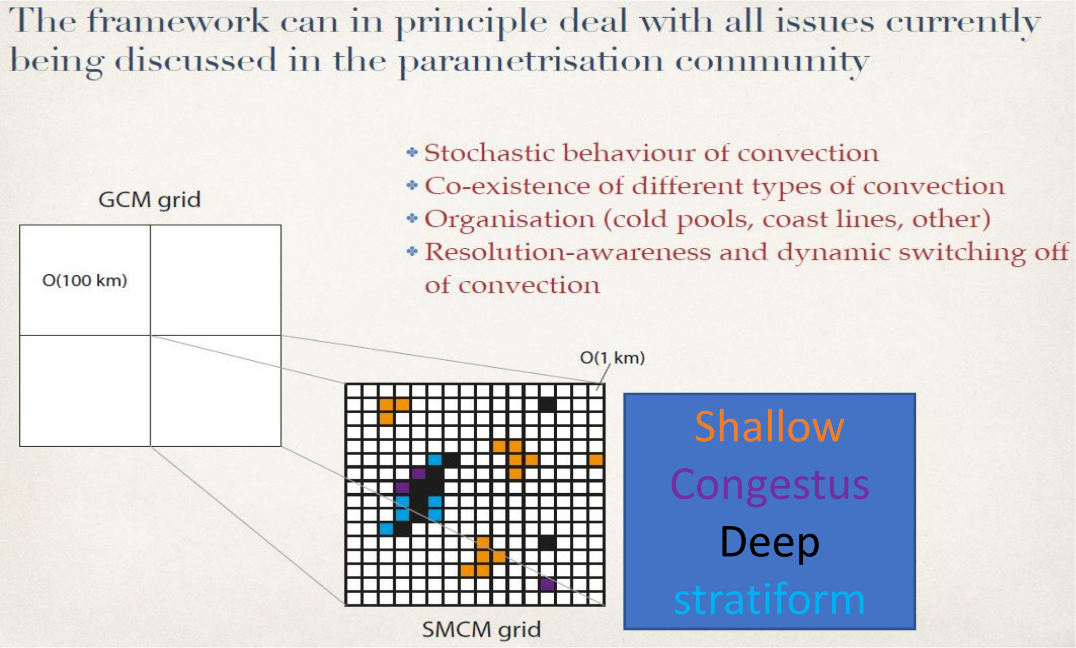
- A clear sky turns into a shallow cumulus site with high probability if there is CIN, or strong large-scale Subsidence
- A shallow site turns into congestus with high probability if there is CAPE and mid troposphere is dry
- A shallow site turns into deep with high probability if there is CAPE and mid troposphere is moist

Transition Rate Functions



Courtesy: Dr. Boualem Khouider

Implementation of the Four-cloud Model in NCEP CFSv2 T126 Model:



Default SMCM (Khouider and Majda 2006; Khouider et.al 2010) considers three types of cloud (congestus, deep and stratiform) and it is implemented in CFSv2 by Goswami et. al 2017.

We have incorporated shallow cloud type along with the three existing cloud types which made the climate simulation more realistic.

Also, all the cloud population statistics are taken from Indian radar data and the stochastic multicloud model (SMCM) is calibrated with radar data.

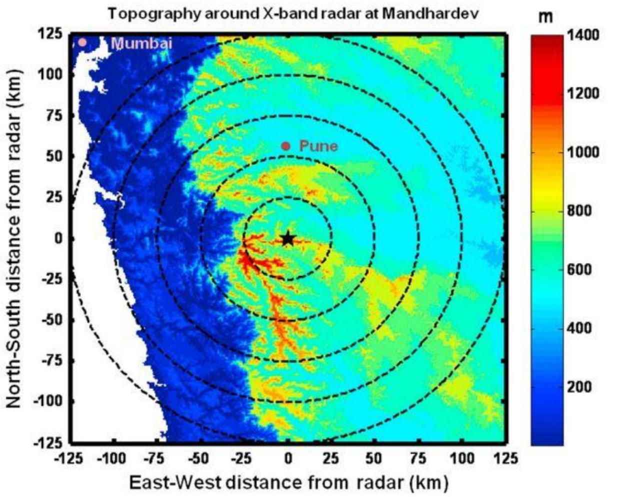


Figure 1. Topography around X-band radar surveillance zone at Mandhardev (18.04°N, 73.85°E, 1290 m altitude) located in the Western Ghats (north-south oriented mountains in the western parts of India). Location of radar is shown by a star symbol. Range rings are shown at 25 km intervals. The Arabian Sea in the map is represented by white color. Locations of two major cities, Mumbai and Pune are shown for the reference. The topography data were obtained from the U.S. Geological Survey data set with a horizontal grid spacing of 30 arc sec (approximately 1 km).

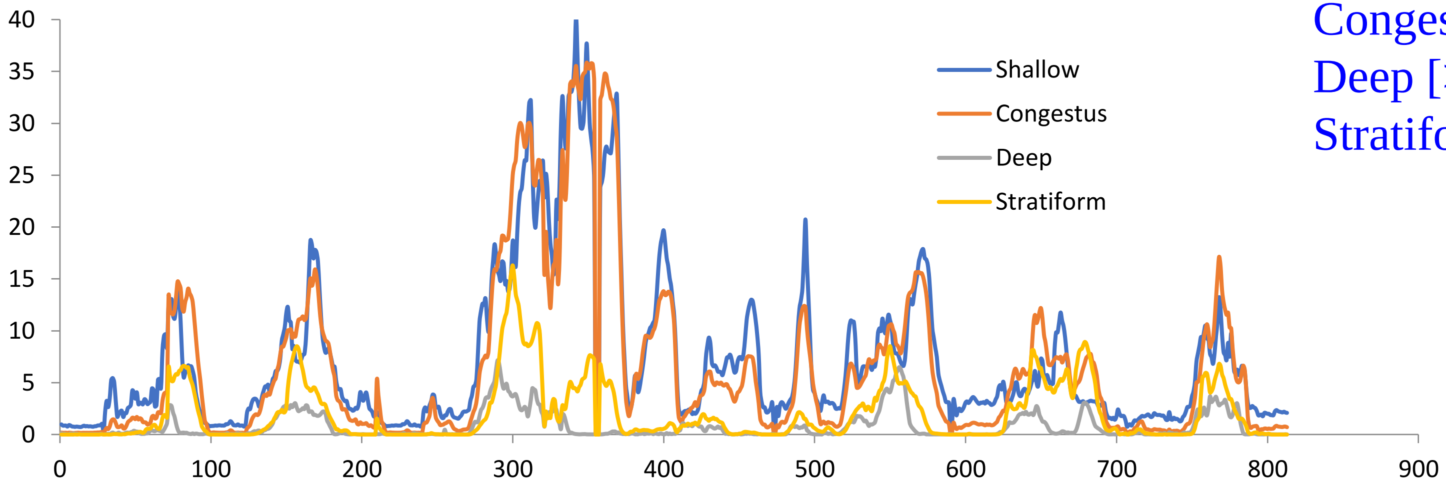
[Adopted from Utsav et al. 2017]

YP Rao's (1976) monograph showed shallow clouds giving copious rain are observed over the Western Ghats on many occasions with their top < 4 km

Konwar et al. (2014) have studied shallow precipitating clouds using microrain radar and disdrometer data at Mahabaleshwar (situated in the Western Ghats).

Further, Deshpande et. al 2015; Utsav et al. 2017 showed dominance of shallow cloud over the Western ghats

Cloud area fraction from Mandhardev Radar data



Shallow [<4.5 km]
Congestus[4-9 km]
Deep [>9 km]
Stratiform [5-15 km]

Methodology:

Input: Cloud population are taken from Mandhardev radar and large scale variables (such as CAPE, CIN, W, D etc.,) are taken from ERA5

The Bayesian inference was utilized in PETSc toolkit, a collection of parallel data structures and methods for scientific computation.

Through The Bayesian inference technique, transition rates are being computed and the timescale values are generated.

Transitional Rates:

$$R_{01} = \frac{1}{\tau_{01}} F(C_N, -W)$$

$$R_{02} = \frac{1}{\tau_{02}} \Gamma(C_L)\Gamma(D)\left[1 - F(C_N, -W)\right]$$

$$R_{03} = \frac{1}{\tau_{03}} \Gamma(C)(1 - \Gamma(D))\left[1 - F(C_N, -W)\right]$$

$$R_{12} = \frac{1}{\tau_{12}} \Gamma(C_L)\Gamma(D)\left[1 - F(C_N-, W)\right]$$

$$R_{13} = \frac{1}{\tau_{13}} \Gamma(C)(1 - \Gamma(D))\left[1 - F(C_N, -W)\right]$$

$$R_{23} = \frac{1}{\tau_{23}} \Gamma(C)(1 - \Gamma(D))\left[1 - F(C_N, -W)\right]$$

$$R_{34} = \frac{1}{\tau_{34}}$$

(Where 0,1,2,3,4 are different states such as clear sky, shallow,…,stratiform)

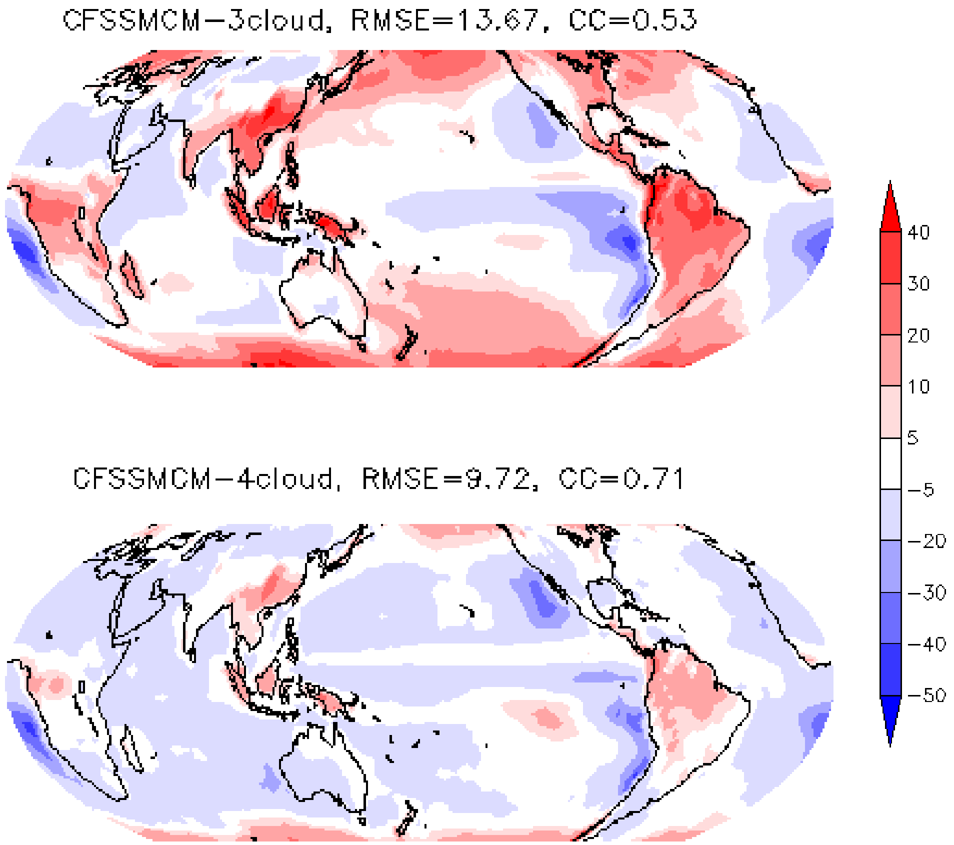
We have trained NCEP CFSv2-SMCM model by using Indian radar (Mandhardev) observations and inferred the transition timescale values by using Bayesian Inference method, and placed the timescale values in SMCM module.

Two climate simulations are being carried out, one with considering all four cloud types (named as 4cld simulations) another excluding shallow cloud type (named as 3cld simulations).

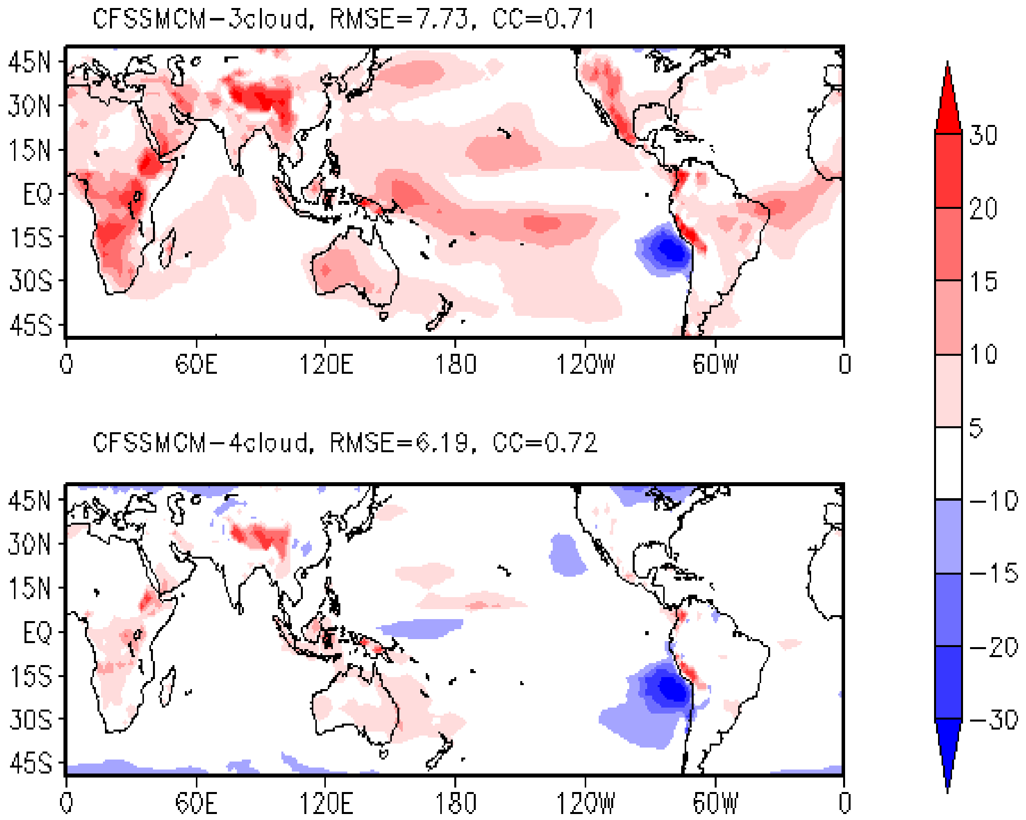
Simulations are done for 25 year and last 20years are analyzed.

Results:-

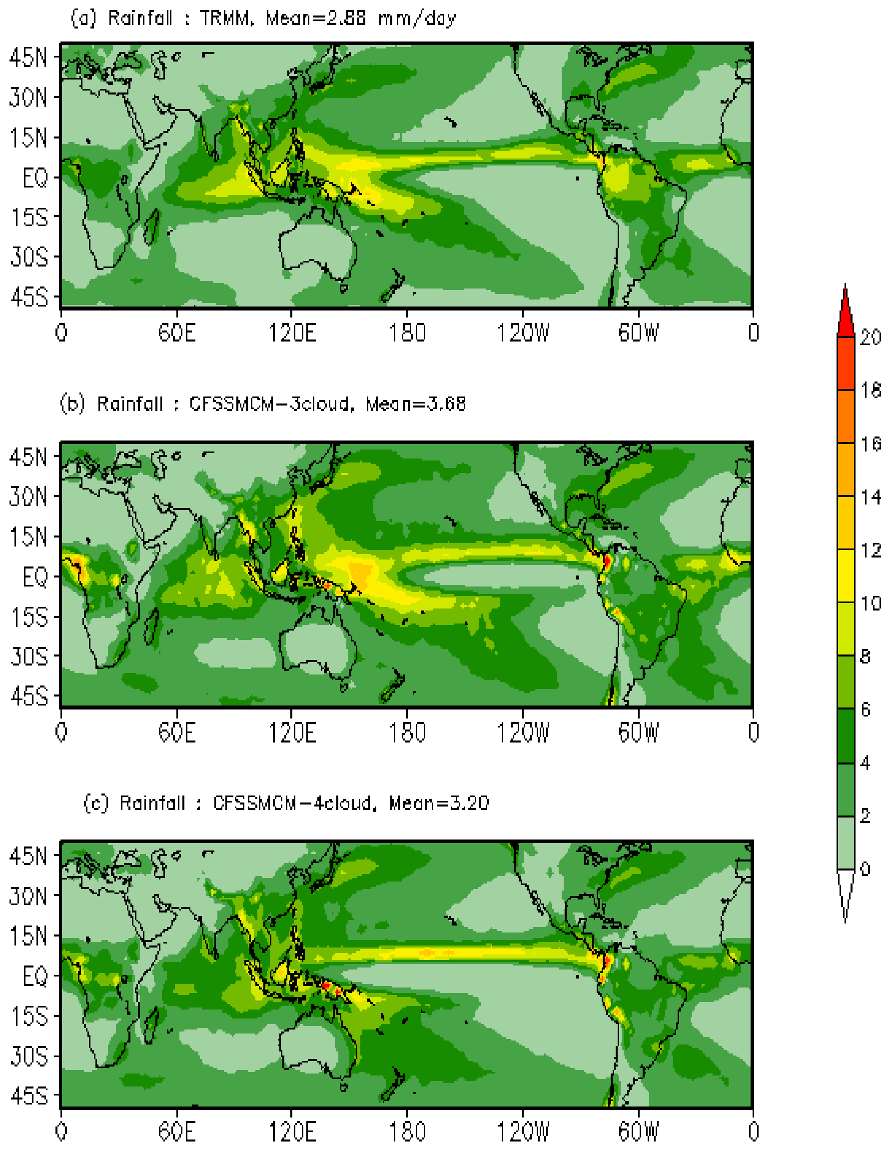
Low-level cloud bias



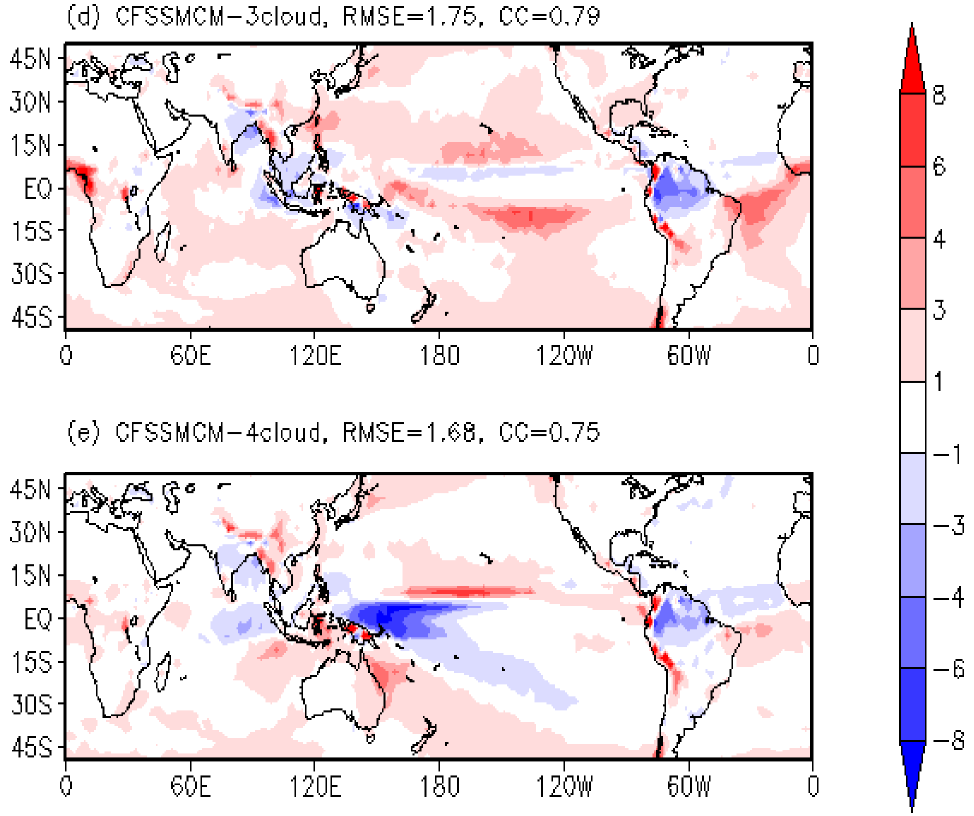
Mid-level cloud bias



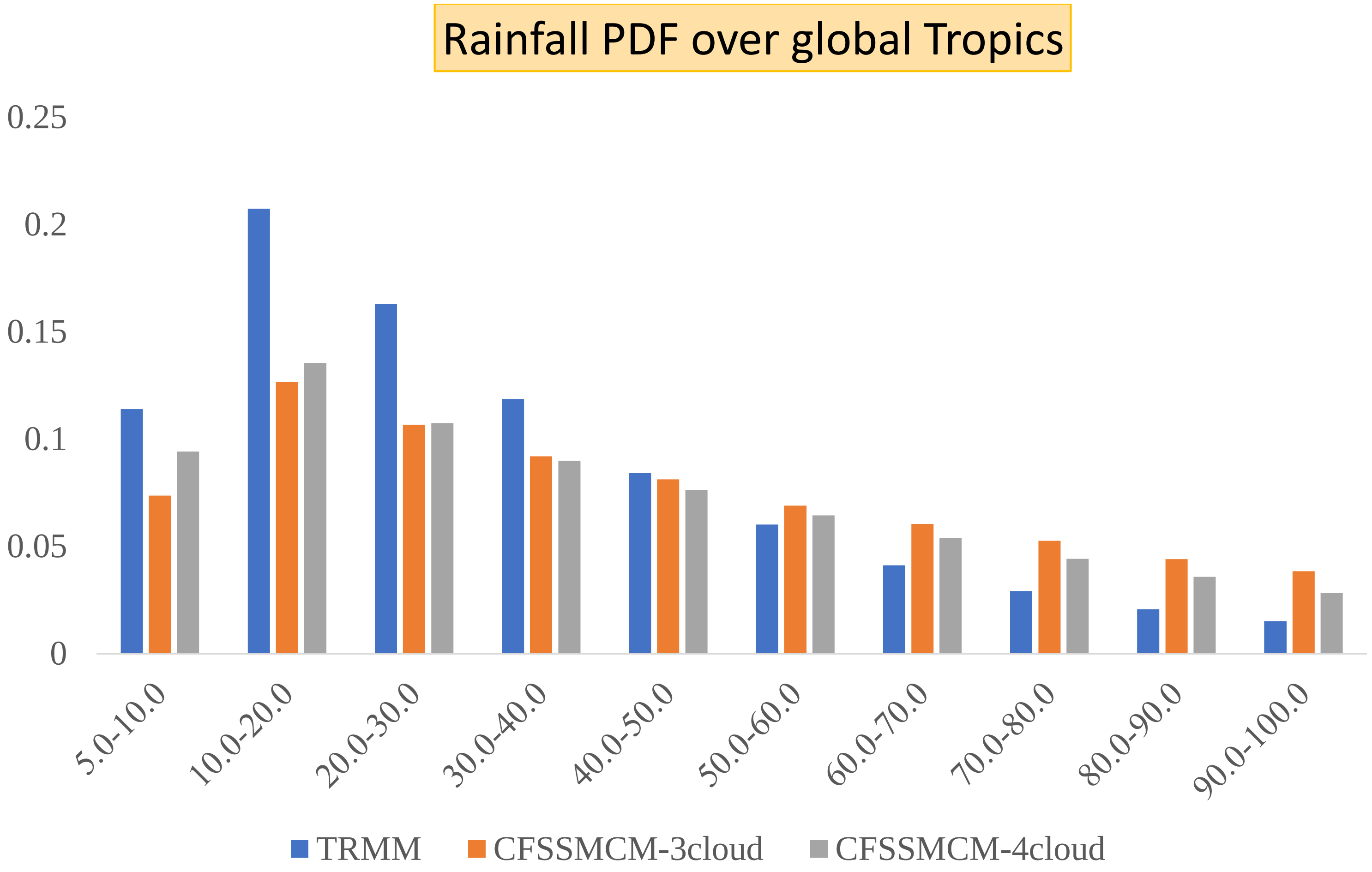
Annual Mean precipitation



Annual Mean precipitation bias

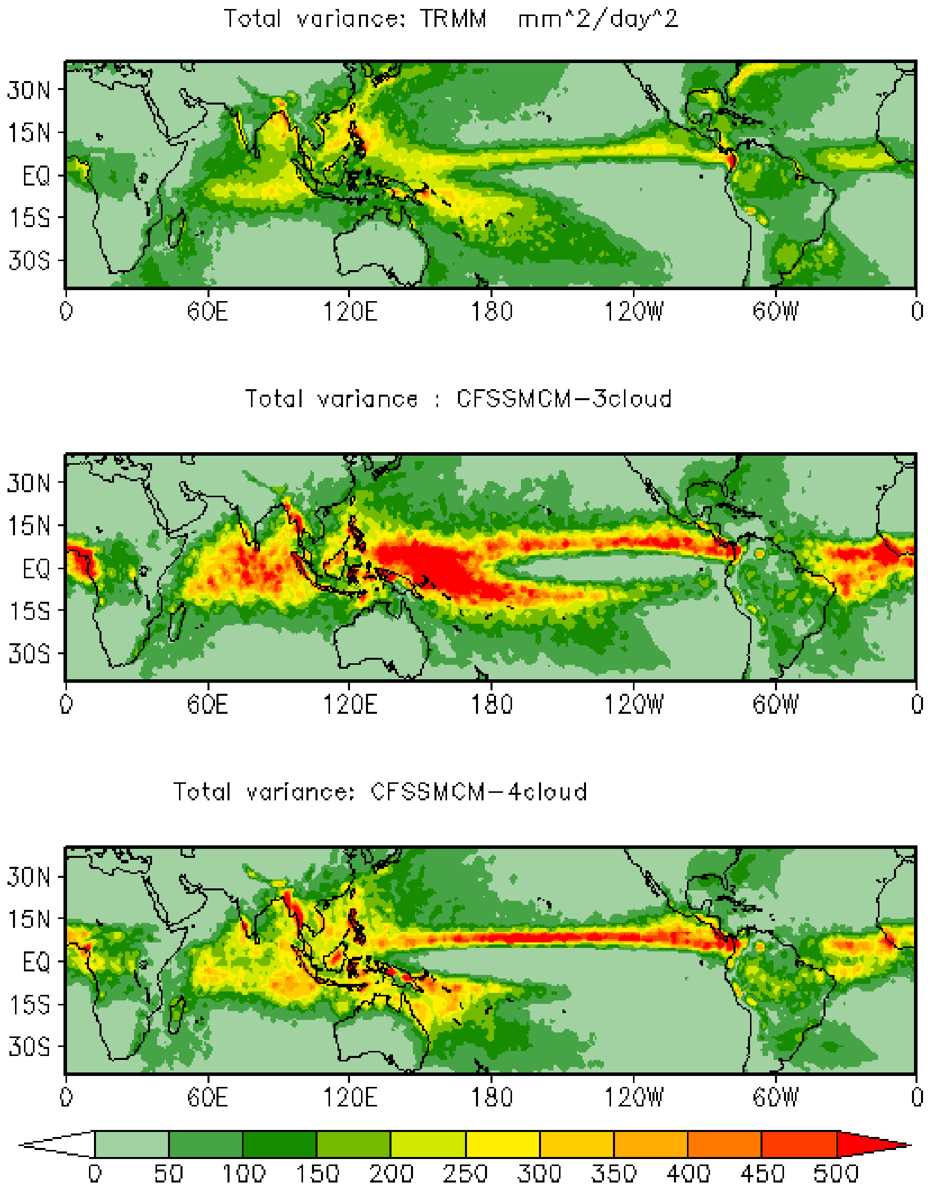


A lots of regional improvement and only one major deterioration: negative bias in the southern equatorial pacific in 4cloud simulation



It is found that 4cld reasonably better simulates the lighter rain-rate categories. PDFs of rainfall beyond 50 mm/ day are also seen to be better simulated by 4cld than 3cld as compared to observations. The 3cld simulated PDF appears to significantly overestimate the heavier categories (> 50 mm day-1) compared to the observations. This result is further supported by the total daily variance plot in next slide.

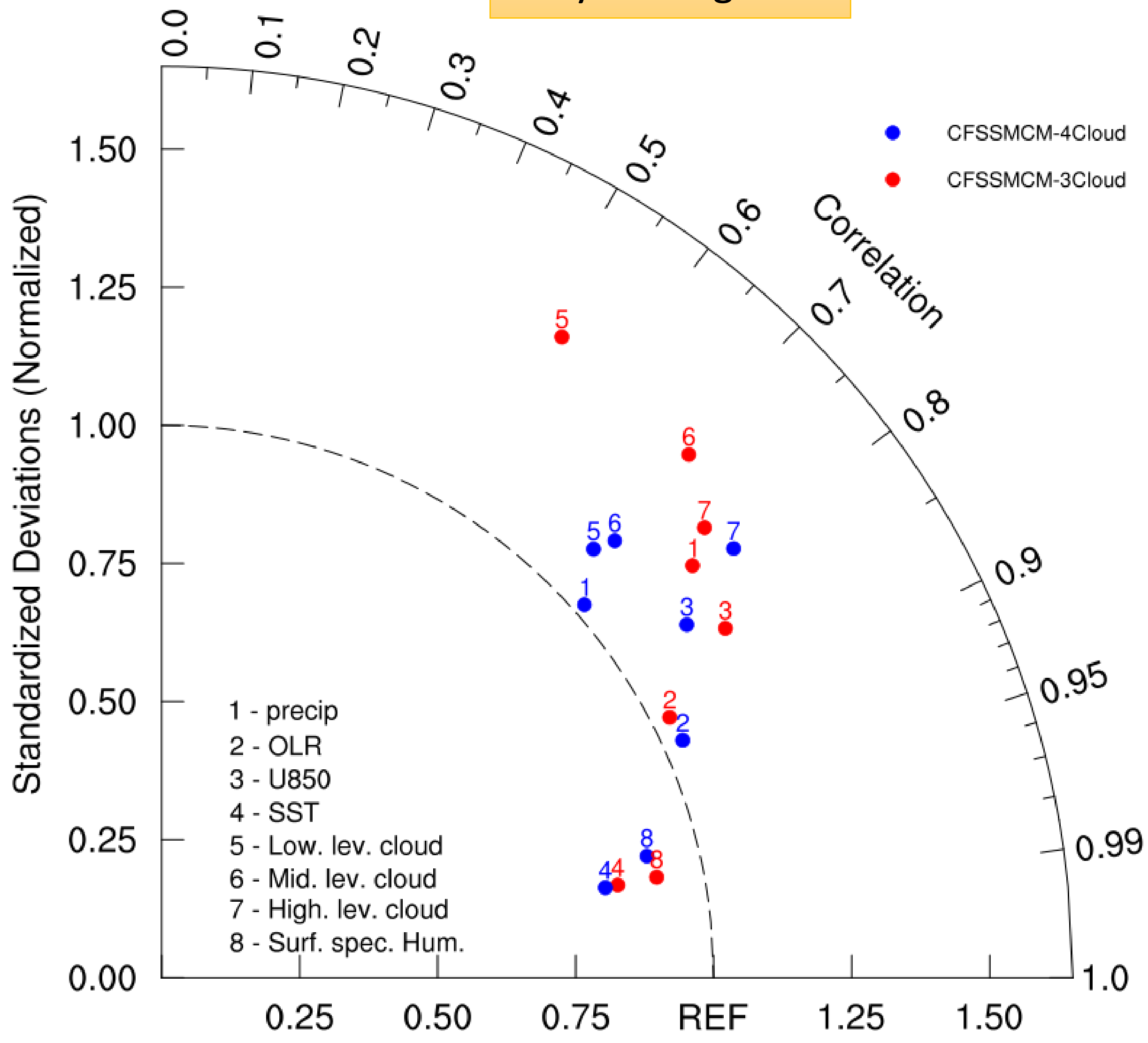
Total variance



Prominent improvement in the double ITCZ structure in 4cloud simulation.

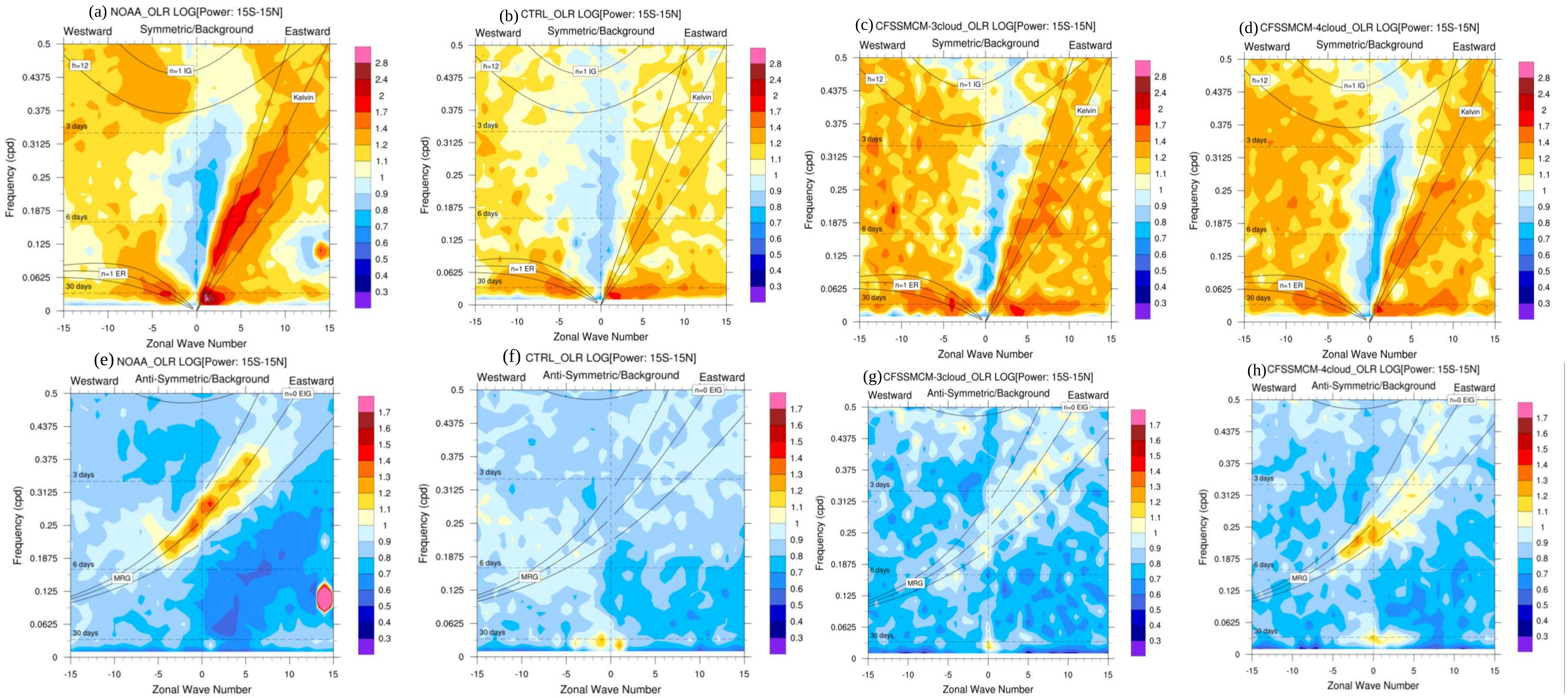
It could be because the 4cloud model is better at capturing low clouds in this region (the negative bias is substantially reduced). But it could also be because the 4cloud model eliminates the positive bias in midlevel clouds over the CP Ocean. It could be rather a combination of the two though!

Taylor Diagram



4cld simulation exhibits a better correlation and improved variabilities for most of the parameters. However, the SST underestimates the variability slightly in 4cld simulation as compared to 3cld simulation.

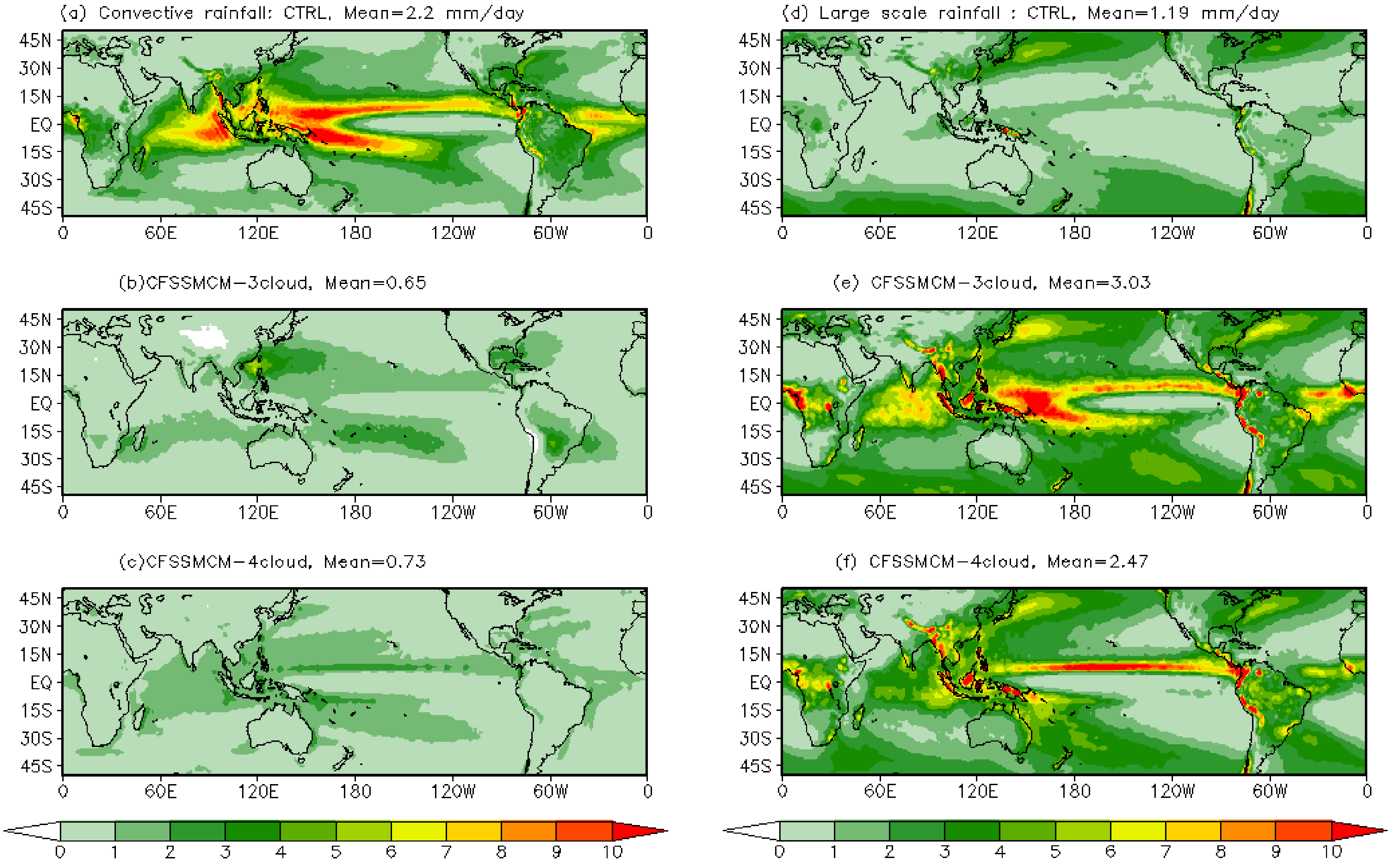
WK spectra of OLR



The simulations show limited fidelity in capturing the CCEW spectrum. The improvement of power in mixed Rossby-gravity waves in 4cld simulation compared to the 3cld simulations is truly noteworthy However, 4cld still needs to insert some more power in the significant modes to match well with the observations.

Convective Rainfall

Large-Scale Rainfall



Summary and Conclusions

- Relative improvement in low and mid-level cloud is noted in CFSSMCM-4cloud and it is supported by lower RMSE values than CFSSMCM-3cloud.

- Overall improvement in the annual mean rainfall with the improvement of double ITCZ in the Eastern Pacific.

- Improvement in the convective and large-scale rainfall .

- This study is the first attempt to calibrate the stochastic version of NCEP CFSv2 with four cloud extension calibrated through observation and check its impact on a GCM.

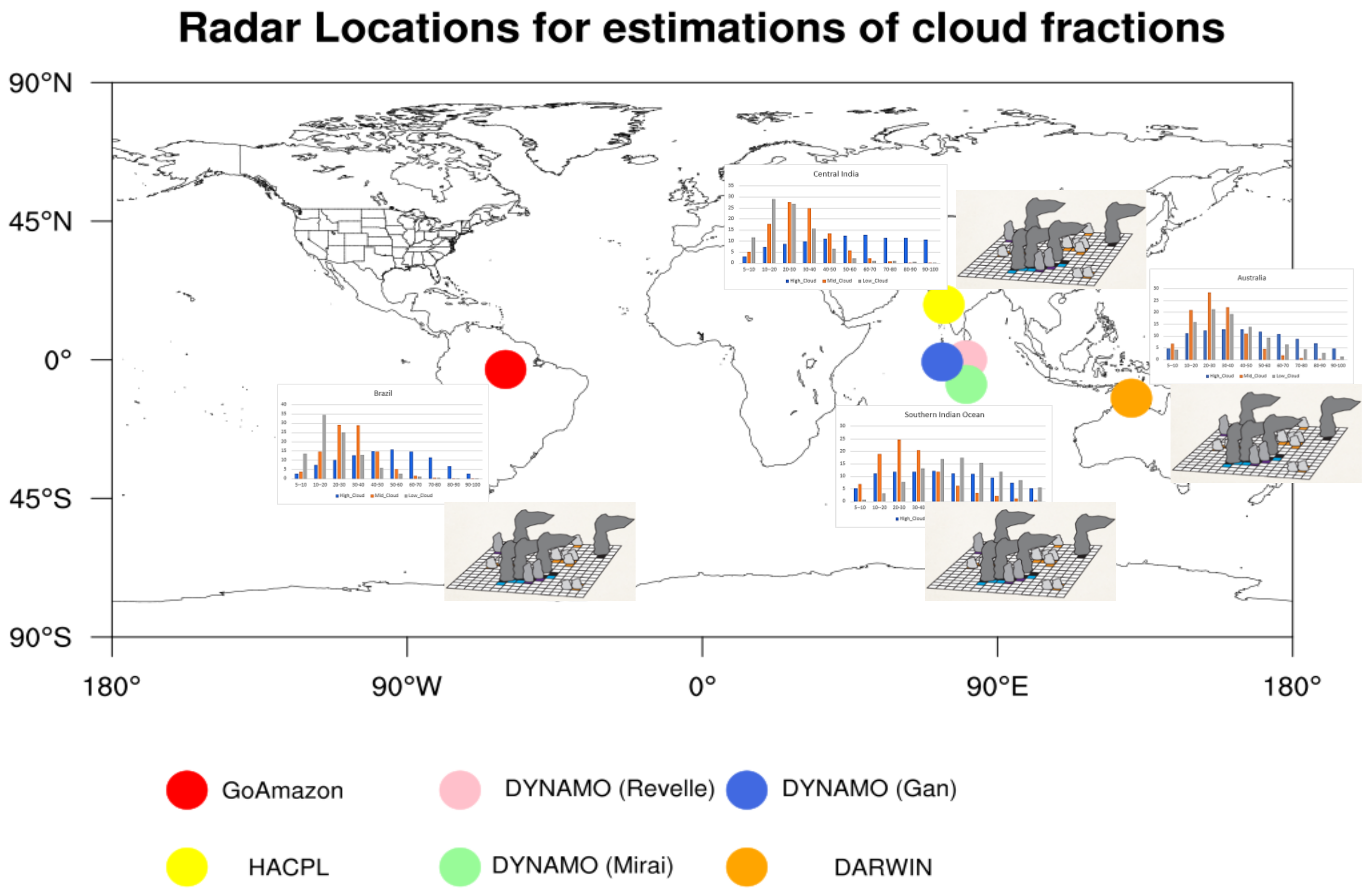
- This study considered the observational data-sets for a concise period to calculate the transition time-scales for the SMCM, which would confidently say that SMCM should use more realistic transition time-scales extracted from actual observations.

- This study concludes the requirement of more observational data-sets across the globe to calibrate GCMs for proper simulation of different aspects of climate.

Constraining the cloud transition probability with global RADAR observations

Problem Statement:

To use a single radar based (earlier LES based) transition probability and applying for all GCM grid is not realistic. Therefore the holistic approach will be collecting radar data from different regions across the globe and it will be utilized to constrain the model (to make the cloud transition probability in the model representative of respective region)



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Dr. Courtney Schumacher (Texas A&M University, USA)
Dr. Michele De La Chevrotiere (Environment and Climate Change Canada)

Future work

CFSSMCM-4cloud convection scheme will be tested in a very high resolution GFS T1534 model in short range operational forecast.

Thank You

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