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Simulation of Inter-annual Variability of Summer Monsoon Rainfall in a GCM over India and Nepal

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Abstract

Monsoon is one of the major phenomena over the entire tropical belt that is associated with the regional climate primarily through rainfall. The importance of the monsoon rainfall is prolonged to a large fraction of the world's population and the socio-economic prospect of the region. Community Atmosphere Model (CAM) (v4, 0.47°×0.63°) developed by NCAR has been used for this study. Two experiments have been conducted; viz. CLIMO Exp. using climatological SST and OBSST Exp. using observed monthly OI-SST. The climatology of surface temperature, wind circulation and rainfall over the extended Indian monsoon (60°E–110°E; 0°N–40°N) region has been generated through 30-year long-term simulation of CAM and analyzed using different observed Climatology viz. TRMM rainfall, NCEP reanalysis, IPCC, UD generated climatology, IMD & DHM in-situ observations etc. The model derived monthly averaged surface temperature climatology over the study region has a good correlation with the observed IPCC and NCEP climatology. Both the simulations are able to capture the sea surface temperature over the Indian Ocean and over the landmass. The model simulation shows heat sink region over the north western part of India and spreads over the eastern part almost reaching Bay of Bengal region and gets slowly reduced after approaching the south west monsoon rains. The seasonal temperature variation over the study region, monthly mean, maximum and minimum are comparable. The climatological wind circulation at 850 hPa and 200 hPa are well simulated. The reversal of wind during pre-monsoon and monsoon season over the region are well simulated by both the experiments. Therefore, this study using high resolution modeled data provides an insight of the model credibility in capturing the climatic variability over the region (India, Nepal and its surroundings) and its capability for predicting the inter-annual variation and projecting the climate of the globe. The present study aims to measure the skill of the state-of-art AGCM in simulation of ISM rainfall and investigate the inter-annual variation using the climatological and observed SST.

Keywords: Monsoon, ISM, IAV, wind, simulation

1. Introduction

During late spring, in April and May, the land over the Indian subcontinent heats up much faster than the surrounding Indian Ocean, creating a strong surface temperature contrast because land and sea respond differently to solar radiation. This contrast helps trigger a seasonal reversal of winds and leads to the formation of a low-pressure belt over northern India known as the monsoon trough, which marks the onset of the summer monsoon. Moist southeasterly winds from the southern Indian Ocean cross the equator and, under the influence of Earth's rotation, turn into southwesterly winds that blow across India, bringing extensive cloud cover and rain typically associated with such low-pressure systems (Kang et al., 2002). When these moisture-laden winds reach the southern tip of the Indian Peninsula, the region's complex topography splits the flow into two main branches: the Arabian Sea branch and the Bay of Bengal branch. The Arabian Sea branch first strikes the Western Ghats along the west coast, where it rises over the mountains and produces heavy rainfall; from there it progresses northward, maintaining wet conditions along the coastal belt west of the Ghats (Das et al., 2012). The Bay of Bengal branch travels over the bay toward northeastern India and Nepal, picking up additional moisture before arriving at the Himalayan foothills with very intense rainfall. On encountering the Himalayan barrier, these winds are deflected westward and then move along the mountain front, shedding large amounts of rain over the plains and hill regions lying to the south of the Himalayas.

The year-to-year variation in the amount of seasonal mean rainfall occurring every year from June to September are the remarkable features of the summer monsoon. Even within a season there is a considerable variation, both in space and time in the rainfall over the region (Krishnamurthy & Ajayamohan, 2010).

The variation of rainfall over space and time has huge impact on the resources that is dependent on rain water for its growth on this region. Almost two thirds of the humanity habitat within the regions influenced by monsoon. Thus, the prediction of the monsoon rainfall well in advance has great significance to the world community. The usability of such prediction at least a season ahead is huge in terms of agricultural, economic and social aspects (Das et al., 2012). This region's economy is highly dependent on agriculture production; Indian economy depends on the monsoon rains. Most of the annual rainfall in this region occurs from June to September (summer monsoon or southwest monsoon) (Gadgil, 2003). The spatial variation of the wind and mean monsoon rainfall over the region (Figure 1).

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The summer monsoon rainfall index over the region of India and Nepal is the weighted average of the June-September rainfall.

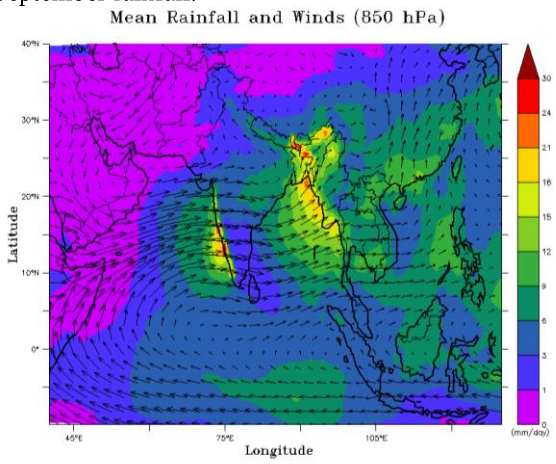

Figure 1: Mean monsoon rain & winds (June – Sept)

During the summer monsoon, some parts of India receive particularly heavy rainfall, especially along the west coast of the peninsula where moist winds are forced to rise over the Western Ghats, and across the northeastern states where hilly terrain similarly enhances rainfall. There is also a broad rain belt centered near 20°N that extends northwestward from the head of the Bay of Bengal, which consistently records substantial monsoon rainfall. Year-to-year changes in all-India summer monsoon rainfall (ISMR) are strongly linked to how much rain falls in this belt, commonly referred to as the monsoon zone (Sikka & Gadgil, 1980; Gadgil, 2003).

Interannual variability of the monsoon refers to how conditions in one monsoon season differ from the long-term average seasonal cycle from year to year. Over the past century, the overall fluctuation in all-India summer monsoon rainfall (ISMR) has been relatively modest, with a standard deviation of only about 10% of the mean (Gadgil, 2003). However, several large-scale climate modes, particularly El Niño–Southern Oscillation (ENSO), also vary from year to year and interact with the monsoon system, sometimes amplifying or altering these variations. Because of this, whether a given year is slightly wetter, markedly drier, or near normal, and how conditions change from one year to the next, can have major socioeconomic consequences both within South Asia and in regions influenced by the monsoon (Wang & Ding, 2006). The year-by-year changes in ISMR for the period 1990–2020 are illustrated in Figure 2.

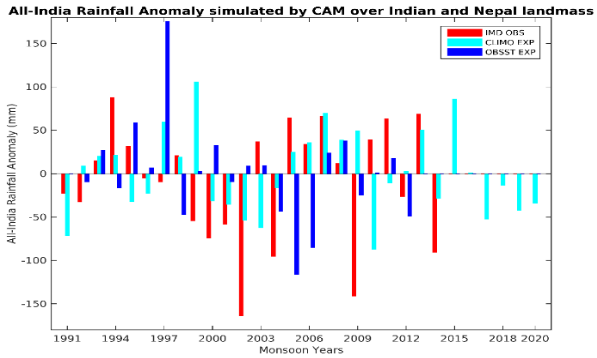

Figure 2: Inter-annual variation of summer Rainfall over India and Nepal during 1991-2012

Indian Summer Monsoon (ISM)

The monsoon is manifested as atmospheric phenomena that interact between atmosphere-land-ocean. Gigantic land-sea breeze due to differential heating of land and sea, first suggested 300 years ago by Hadley (1986) is still considered as the basic mechanism of monsoon (O'hare, 1997). The major difference between the characteristics of ocean and land is that the former has large heat content with longer climate memory of more than a year, whereas the heat content capacity of land is small and believed to have a shorter climate memory of less than a season. Therefore, unlike the oceanic surface, the land surface experiences a strong rapid heating and cooling within a seasonal cycle that indeed affects a number of atmospheric processes through modifying the atmospheric heating or cooling. The land surface processes are equally responsible for inter-annual variability of the monsoons along with several oceanic large-scale processes like ENSO, IOD etc.

Another hypothesis of the monsoon system is the seasonal migration of the ITCZ (Charney, 1968) resulting in shift of equatorial trough (Riehl et al., n.d.) in response to the seasonal variation of the latitude of maximum insolation. The low-pressure trough at sea level that is a part of the global equatorial trough of the northern summer season known as the monsoon trough is one of the nine parameters identified by (Krishnamurti and Bhalme 1976, n.d.) in defining the monsoon system in broad-scale. Mascarene high, low-level cross-equatorial jet, Tibetan high, tropical easterly jet, monsoon cloudiness, monsoon rainfall, dry static stability and moist static stability are the other parameters mentioned. The northward progress of ITCZ also has its own intra annual variation that is largely controlled by the southern oscillation. The ITCZ could migrate far up to the northern sub-continent territory of Nepal.

Monsoon over Nepal

Nepal lies between latitudes 26°22' and 30°27'N and longitudes 80°04' and 88°12'E. This geographic span results in diverse altitudes, ranging from around 60 meters above sea level in the southern plains, known as Terai, to the peak of Mount Everest at 8,848 meters in the northeast. Of the country's total area of 147,516 km², approximately 86% consists of hilly and mountainous terrain, while only 14% is flatland. The rapid changes in elevation and geographical features create a variety of climatic conditions across the nation. Consequently, within just 200 kilometers, Nepal experiences nearly every climate type, from subtropical to alpine and arctic conditions. Temperature variations are largely influenced by the topography, particularly from south to north. Most precipitation, about 80%, occurs during the summer monsoon, with winter rains more prevalent in the western hilly regions. The dominant monsoon rains shape the seasonal distribution of precipitation, which is categorized into four seasons: monsoon (June to September), post-monsoon (October to November), winter (December to February), and pre-monsoon (March to May) (Dai et al., 2023). Nepal's climate is primarily influenced by altitude, terrain, and seasonal atmospheric patterns (Thakuri et al., 2019; Sapkota et al., 2025). Analyzing historical climate data is crucial for comprehending current climate trends, changes, natural variability, and extreme weather events at localized levels. This analysis is vital for evaluating the impact of climate change across various sectors in Nepal (ADB Nepal Strengthening Capacity for Managing Climate, n.d.).

During the monsoon season, prevailing winds across the country are mainly from the east, originating from the moisture-rich Bay of Bengal. As these humid winds encounter the Himalayan Mountain range, they are deflected westward, resulting in significant rainfall as they traverse the Indo-Gangetic plains (Das et al., 2012). In Nepal, the summer monsoon typically begins in the second week of June and lasts until late September or early October, marking the period with the highest precipitation, accounting for approximately 80% of the country's annual rainfall (about 79.8–80.5%). The eastern regions of Nepal generally experience more intense rainfall, while the western areas, particularly the northern regions of the mid-west, tend to be drier (Marahatta et al., 2009). Some districts, such as Kaski, Sindhupalchok, and Sankhuwasabha, are noted for their significant rainfall during this season, whereas trans-Himalayan districts like Mustang, Manang, and Dolpa receive less than 150 mm. In contrast, Kaski can see rainfall exceeding 4,500 mm in one monsoon period (DHM, 2015). Temperatures are at their lowest during winter and gradually increase through spring, with May or early June usually being the warmest before the cooler monsoon rains arrive. Temperature variations are heavily influenced by season and altitude: the southern Terai plains are the hottest, while the northern mountainous regions are the coldest. In winter (December–February, DJF), minimum temperatures in the northern high mountains can drop below -10°C (DHM, 2015).

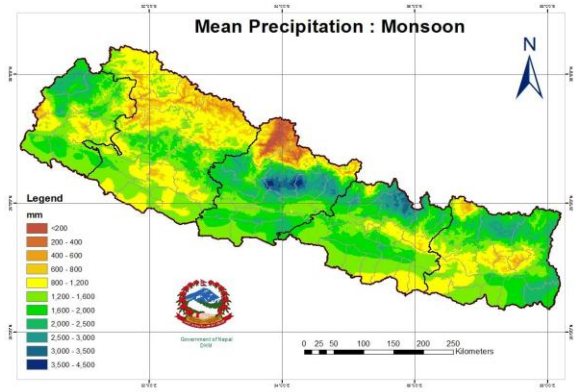

Figure 3: Mean Monsoon precipitation variation over Nepal

The seasonal mean maximum temperatures are highest in the pre-monsoon (MAM) reaching 36ºC along the southern tips of central Nepal.

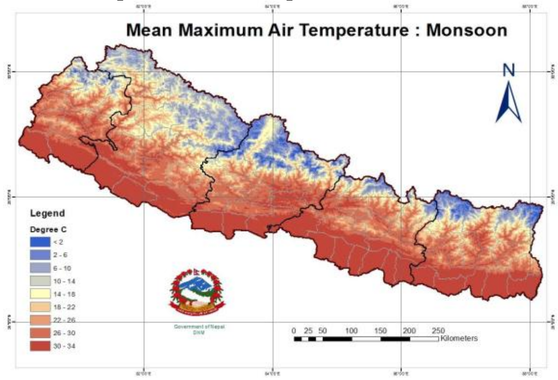

Figure 4: Mean Monsoon Maximum air temperature variation over Nepal

Between these extremes, monsoon months (June–September) are slightly warmer than the post-monsoon season (October–November) in terms of both daily maximum and minimum temperatures. During the monsoon, maximum temperatures above 32°C are common over the southern plains, and in most other parts of Nepal monsoon maxima are above 22°C, except in the narrow, highest-elevation belt along the northern border. Throughout the year, the western Terai generally records slightly lower maximum temperatures than the eastern Terai, suggesting more frequent cloud cover in the west due to the influence of western disturbances (DHM, 2015).

Climate Model for Inter-annual Variability of ISM

The internal year-to-year variability of the Indian summer monsoon (ISM) mainly arises from interactions within the coupled ocean–atmosphere system. In this coupled system, the atmosphere is the primary driver of high-frequency fluctuations, while coupling with the ocean can modify but not dominate these atmospheric variations (Goswami & Xavier, 2005). To understand this internal interannual variability (IAV), it is therefore essential first to examine how the atmosphere on its own can generate such changes from one year to the next. To study these processes in a realistic way, Goswami and Xavier (2005) developed and used a coupled atmosphere–

ocean general circulation model specifically designed to simulate the ISM and its internal variability.

The coupled climate model has four major components viz. atmosphere, land, ocean and sea-ice interacting each other at specific time intervals. CCSM developed by NCAR is one of such coupled models studied worldwide (Kiehl & Gent, n.d.; Collins et al., 2006; A. Dai & Trenberth, n.d.). Community atmosphere model (CAM) and community land model (CLM) are two major components of CCSM that have been used in this study. The teleconnection of ISM to the tropical Pacific are well simulated in CCSM; however, there is very little realistic intra-seasonal monsoon variability captured in the long-term simulation of CCSM (Meehl et al., 2006).

Across the Indian subcontinent, one of the most prominent seasonal climate systems is the Indian Summer Monsoon (ISM), also known as the southwest monsoon, which typically spans from June to September. It is a major component of the global hydrological cycle, transporting vast amounts of moisture and delivering widespread rainfall over South Asia. Although the onset over the southern tip of peninsular India generally occurs in early June with a fairly regular seasonal reversal of low-level winds over the Arabian Sea from year to year, the associated rainfall still shows strong intra-seasonal (within-season) and interannual (year-to-year) variability across the region (Krishnamurti & Bhalme, 1976; Madden & Julian, 1994). A key physical driver of the ISM is the thermal contrast between land and sea: because land heats and cools more rapidly than the adjacent ocean, pressure gradients develop that generate and maintain the monsoon winds (Charney & Shukla, 1981; Das et al., 2011).

Region of Study

The distinguishing attribute of the monsoonal regions of the world is considered to be the seasonal reversal in the direction of the wind. The monsoonal region delineated on the basis of significant change in the wind direction between winter and summer extends over a large are part of the tropics, namely, 25 ^{o} S to 35 ^{o} N, 30 ^{o} W to 170 ^{o} E (Ramage, 1971).

Near the center of this monsoonal region is the Indian subcontinent and the ocean surrounding it, which experiences large seasonal variation in the wind direction. A southeasterly wind from the southern Indian Ocean crosses the equator and gets deflected by the Earth’s rotation to become a southwesterly wind flowing over India, Nepal and its surrounding regions. This study is focused on the monsoon over the extended Indian region i.e. 60^{o}E – 110^{o}E and 0^{o} N–40^{o} N. This region experiences the large seasonal variation in temperature, wind circulations and rainfall between the winter and summer season. The study focused on the landmass of the Indian sub-continental region which is shown in the figure above marked with red color.

2. Objectives

The present study aims to measure the skill of the state-of-art AGCM in simulation of ISM rainfall using the climatological and observed SST. Also, the objective of the present study is to attempt to unravel the internal IAV of ISM generated by atmosphere. The main objectives of the study are as follows:

- Demonstrate the model capability in simulation of summer monsoon rainfall over India and Nepal
- Study the inter-annual variability of summer monsoon rainfall simulated by the CAM model
- Investigate the role of wind circulation over the inter-annual variation of simulated summer monsoon rainfall.

3. Methodology

3.1 Community Atmosphere Model (CAM) and Data Used

In the past twenty years, the National Center for Atmospheric Research (NCAR) has created a flexible three-dimensional global atmospheric model that is extensively utilized for examining and forecasting weather and climate. The latest iteration, version 4.0 of the Community Atmosphere Model (CAM4), represents the seventh generation within NCAR’s atmospheric modeling framework (Neale et al., 2013). CAM4 forms the atmospheric component of the Community Climate System Model version 4 (CCSM4), which integrates the atmosphere, ocean, land, and sea ice (Gent & Danabasoglu, 2011). Within CCSM4, CAM4 can operate with specified sea surface temperatures, including slab-ocean configurations, or in a fully coupled mode that incorporates interactive surface components like the Community Land Model (CLM) and the Los Alamos Sea Ice Model (CICE), thus facilitating a wide array of climate experiments (Gent & Danabasoglu, 2011; Neale et al., 2013).Compared to its predecessor, CAM3, CAM4 incorporates significant yet moderate adjustments in configuration, particularly in the parameterization of deep convection (Collins et al., 2006; Neale et al., 2012). These enhancements in physics considerably refine the simulated mean climate and address persistent tropical biases, leading to more accurate representations of patterns and variability in the El Niño–Southern Oscillation (ENSO) and improved modeling of the Madden–Julian Oscillation (MJO) (Deser et al., 2012; Subramanian et al., 2011; Neale et al., 2013). Furthermore, CAM4 upgrades its horizontal resolution from spectral T85 (approximately 1.4° at the equator) to a standard 1° grid using a finite-volume (FV) dynamical core, which is now the default setting (Neale et al., 2013). Additionally, CAM4 presents an alternative spectral-element (SE) dynamical core based on the High-Order Method Modeling Environment (HOMME), which features a nominally unstructured grid (CAM4-SE) (Dennis et al., 2012; Neale et al., 2013). Preliminary evaluations indicate that CAM4-SE delivers climate simulations with performance akin to

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that of the standard FV-based CAM4 (Evans et al., 2013; Mishra et al., 2011; Neale et al., 2013).

3.2 Data

Different types of data viz. satellite observations, derived climatology, model reanalysis products and in-situ observations have been used for the present study as per the requirements.

The initial state and the boundary conditions for the atmosphere and land component of the model have been prepared from different satellite observations and NCEP reanalysis product. Satellite observations are used for model validation and simulation. All the required atmospheric initial fields taken from NCEP GFS for the model simulations have the resolution of 0.47°×0.63°.

rainfall climatology (3B42 and 3B43) has been used to validate the bias corrected model rainfall.

The Global Precipitation Climatology Project (GPCP) monthly rain rate from 1991 to 2012 has been used to remove the simulated rainfall bias. GPCP established by World Climate Research Programme to quantify the distribution of precipitation around the globe over many years.

Meteorological parameters viz. Temperature (maximum and minimum), precipitation and wind from large number of ground observations over Nepal for the duration of 1991 to 2012 have been used for the validation purpose of the study. A case study for the validation of the model simulated data for both CLIMO Experiment and OBSST Experiment data has been done in this paper.

Table 1: Different Data Types used in the study

Data type	Data source	Data used for
NCEP-GFS Reanalysis	NCEP	Preparation of Model Initial Conditions
Optimum Interpolation SST (monthly)	NOAA	Preparation of Model Boundary Conditions
Climatology of wind circulation at different pressure levels	NCEP Reanalysis	Validation of model climatology
GPCP Rainfall (monthly)	GPCP	Model simulated rainfall bias correction
TRMM 3B42 daily and 3B43 monthly	TRMM	Validation of model generated rainfall climatology
1°×1° gridded rainfall over Indian region	IMD	Validation of model simulated rainfall
0.5°×0.5°gridded temperature	UD	Validation of model simulated temp.
0.5°×0.5° gridded temperature	IPCC	Validation of model simulated temp.

Wind, temperature and pressure profiles have been interpolated along the horizontal as well as vertical pressure levels. For the long-term climatological simulations, the model has been initialized with the climatological atmospheric states consist of the essential prognostic variables only. These Initial Conditions (ICs) does not have any impact on the long-term CAM simulations due to the fact that the impact of atmospheric ICs last only for the 10 to 15 days of the model simulation (Das et al., 2015); however, in this study, the spin-up time allowed to achieve the model stability has been considered up to 1 year of model simulation.

The model simulations have been analyzed and validated with different satellite derived observations, IMD observed in-situ measurements and global model reanalysis products. The model generated temperature, wind and rainfall climatology have been validated with University of Delaware (UD) generated long-term temperature climatology of 0.5°×0.5° gridded datasets, NCEP-GFS reanalysis generated zonal and meridional climatological wind profile and observed rainfall climatology of Tropical Rainfall Measurement Missions (TRMM) and rainfall climatology generated from the 0.5°×0.5° gridded in-situ (measured and interpolated) rainfall over land by Indian Meteorological Department (IMD) for the period of 1991 to 2012. Since IMD generated gridded rainfall is available only over the Indian landmass, the TRMM rainfall climatology is used here for the validation over land as well as over the ocean. TRMM generated

3.3 Long Term Simulation of ISM

To study the Indian summer monsoon (ISM) over long periods, a global climate model is first driven with observed monthly sea surface temperatures (SSTs) so that its simulated monsoon climatology and interannual variability (IAV) resemble observations. The model is then integrated for an extended period without externally imposed year-to-year forcing. If, under these conditions, the simulated internal IAV of the ISM has a substantial amplitude and its spatial pattern resembles the observed IAV, the simulations can shed light on the origins of the monsoon's internal variability (Goswami & Xavier, 2005).

Using this framework, Goswami and Xavier (2005) tested the hypothesis that intra-seasonal oscillations (ISOs) of the monsoon are a major source of internal IAV. ISOs can influence the seasonal mean and its variability in several ways. When the spatial pattern of an ISO mode projects strongly onto the seasonal-mean rainfall pattern and the ISO anomalies follow a non-Gaussian, positively skewed distribution, the seasonal average of these anomalies (a "seasonal ISO bias") can either strengthen or weaken the mean monsoon. Rainfall anomalies over the monsoon region are known to have a skewed, binomial-like distribution, in which the variance is roughly proportional to the mean; ISO-scale rainfall anomalies largely retain this behavior (Das et al., 2012; Goswami & Xavier, 2005). As a result, ISO amplitude scales with the seasonal-mean ISO anomaly, and the resulting seasonal ISO bias generated by this nonlinear relationship contributes directly to interannual variations of the seasonal-mean ISM (Goswami & Xavier, 2005).

3.4 Experiment Design

Our primary objective is to study the IAV of ISM, a continuous long term, two sets of simulation of CAM for 30 years and 22 years has been conducted in this study. The first set of simulation named CLIMO Exp. has been carried out for the duration of January 1990 to December 2020 in F05_g16 (0.47°×0.63°) model resolution and the second set of simulation named OBSST Exp. has also been carried out for the duration of 1990 January to 2012 December in the same resolution as CLIMO Exp. The CLIMO Exp. has been conducted using climatological SST so that the realistic IAV of ISM without any external forcing can be differentiated significantly and/or its spatial structure bear some similarity to that of the observed IAV, the model simulations could also provide insight regarding the origin of internal variability of the ISM. The OBSST Exp. has been conducted using mid-monthly OI-SST (0.47°×0.63°) to make sure that the model has a reasonable monsoon climatology and inter-annual variability for a reasonable long period with external inter-annual forcing.

The amplitudes of the inter-annual variability in both these parameters are also compared. For this purpose, the inter-annual anomalies of the seasonal mean for both observations and simulations are derived in following way:

Let $P_{i,j}(x,y)$; i= 1,2…N; j=1,2,…M be the variable of interest, where N=365 days and M=Number of years used in the analysis (M=30 for CLIM Exp, M=22 for OBSST Exp.). The June to September seasonal (JJAS) mean for each year is defined as

$$\bar{P}j\ (x,y) = \frac{1}{122}\sum_{i=1\ june}^{30\ sept} P_{i,j}(x,y),\ \text{j = 1,2,…M} \qquad (1)$$

The climatological seasonal mean may be calculated as

$$\bar{\bar{P}}(x,y) = \frac{1}{M}\sum_{j=1}^{M} \bar{P}j\ (x,y), \qquad (2)$$

And the inter-annual anomalies of the seasonal mean is defined as

$$\bar{P}'(x,y) = \bar{P}j\ (x,y) - \bar{\bar{P}}(x,y)\ ,\ \text{j=1,2,…..M} \qquad (3)$$

The inter-annual anomalies of the seasonal mean calculated in this manner from the CLIM simulations represent pure "internal" variability of the seasonal mean. Those calculated from OBSST and observations, however, represent 'total' IAV containing contributions from both ''internal'' and ''external'' forcing (Goswami & Xavier, 2005).

3.5 Rain-Bias Correction

A statistical rainfall bias-correction method, following Das et al. (2012), is applied to reduce systematic errors in CAM-simulated precipitation over the Indian monsoon region. Sensitivity experiments show that the model tends to produce unrealistic, quasi-stationary rainfall patches over land and adjacent ocean, with nearly identical intensity and spatial patterns from year to year. At F05_g16 resolution (about 0.47° × 0.63°), the climatological CAM rainfall clearly reveals biased regions—particularly over the Arabian Sea, India's west coast, the eastern Bay of Bengal coast, northeastern India, and Nepal—when compared with GPCP observational climatology. This motivates a systematic bias correction. To construct the correction fields, long continuous simulations from 1990 to 2012 are carried out using both climatological SST and observed mid-monthly OI-SST to generate monthly and daily model climatologies. The CAM rainfall climatology is then collocated with the GPCP-derived climatology, and for each grid point (i,j) and each month m=1,2,…,12, a correction term (Pm)ij is computed, representing the model-observation difference to be removed from the raw CAM output.

$$(P_m)_{ij} = \frac{(X_m)_{ij} - (Y_m)_{ij}}{(X_m)_{ij}}$$

Here, $(X_m)_{ij}$ denotes the CAM rain climatology whereas $(Y_m)_{ij}$ denotes the GPCP rain climatology, for the grid box (i,j) and months {m = 1,2,3, …, 12}. In case of $(X_m)_{ij} << (Y_m)_{ij}$, i.e., the simulated rainfall is much lesser than the observed one, we consider $(X_m)_{ij}$ $(P_m)_{ij}$ = -1.0. This assumption confines the correction component -1 --≤ $(P_m)_{ij}$ ≤ 1.0. The grid box (i,j) has positive rain bias if 0 < $(P_m)_{ij}$ ≤ 1.0. and negative rain bias if -1.0 ≤ $(P_m)_{ij}$ < 0. Rain bias correction has been done for each simulation using the relation:

$$\left(R_m^{\mathrm{mod}}\right)_{ij} = (R_m)_{ij} - (P_m)_{ij} * (R_m)_{ij}$$

Here, $(R_m)_{ij}$ is the raw rain simulated by the model and $\left(R_m^{\mathrm{mod}}\right)_{ij}$ is the bias corrected model rain. Positive bias suppresses the rain rate for the grid box whereas the negative bias enhances the same for each model simulation.

The bias-correction fields are applied to both climatological simulations, CLIMO EXP. and OBSST EXP., to adjust the model-simulated rainfall. Bias-corrected outputs from 1991–2020 (CLIMO) and 1991–2012 (OBSST) are then used to construct updated rainfall climatologies. Because GPCP data are used to diagnose the original model bias, the corrected simulations naturally tend to agree closely with the GPCP rainfall climatology (Das et al., 2012). To provide independent verification, the bias-corrected rainfall is further evaluated against TRMM-based climatological observations.

4. Results

4.1 Modal Climatology of Indian Summer Monsoon: Surface temperature

The long term monthly averaged surface temperature has been generated from the CAM simulation in CLIMO Exp. and OBSST Exp. in F05_g16 resolution. One simulation has been done for 30 years (i.e. CLIMO Exp.) and the other for 22 years (i.e. OBSST Exp.) for the time period of January 1990 to December 2020 and January 1990 to December 2012. The spatial and temporal distribution of the long-term monthly averaged surface temperature simulated by CAM model has been analyzed using the NCEP long-term climatology. The spatial pattern of the long-term

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averaged surface temperature during the pre-monsoon (i.e. May), first part of the monsoon (i.e. June, July) and the remaining part of the monsoon (i.e. August-September) have been compared with the observed climatology shown in Figure 6.

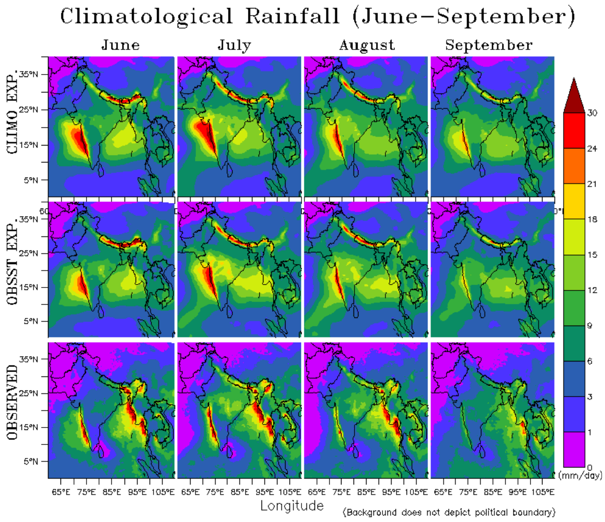

Figure 5: Long term monthly rainfall climatology simulated by CAM; CLIMO Exp., OBSST Exp. (bias) for June to September and TRMM observed rainfall

The model is well simulated and is able to capture the feature over the extended monsoon region (60° E - 110° E; 0° N - 40° N). During the pre-monsoon season (i.e. May), the temperature over the oceanic region is well simulated by the model and is quite near to the observed one. But when it comes to the inner continental regions, the high temperature over the western side of India is spread over the central part and proceeded towards the east coast of India during May.

The temperature of this region as in model simulated is high as 308° K – 310° K which is slightly overestimated to the observed one. The observed spread of heat is limited than the model simulation in the inner continents and protruding towards the east and southern coast of India. In Nepal, altitude plays a major role in the temperature. The southern part of the country has temperature of 300° K – 304° K simulated by model, and the observed has 292° K – 295° K. From this it can be inferred that the model has over-estimated the temperature over the region. Similarly, to the central part of the country the model temperature is 292° K – 295° K, which is quite near to the observed one. And in case of further northern part of the country, the model has overestimated over the observed one.

The lower right of Figure 7 shows that the temperature by the OBSST Exp. is slightly overestimated to the CLIMO Exp. however, the oceanic part is well simulated by both. The heat lock originated during month of pre-monsoon gets shrink towards the western parts of India as monsoon onset occurs and as monsoon gets propagated in June, the hotter continental region gets relief by reducing the temperature.

This phenomenon can be clearly seen in observed climatology as well as the simulated climatology. During this month also, it is seen that the temperature by the OBSST Exp. is overestimated to the CLIMO Exp. being CLIMO Exp. near to the observed one.

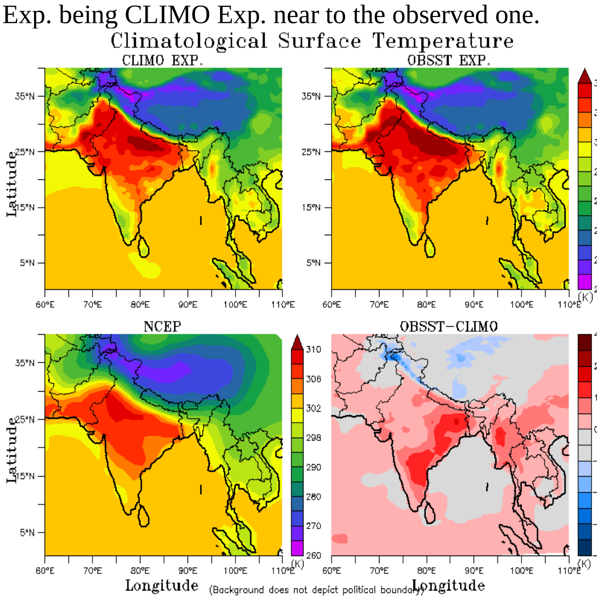

Figure 6: Long term climatology of surface temperature; for the month of May

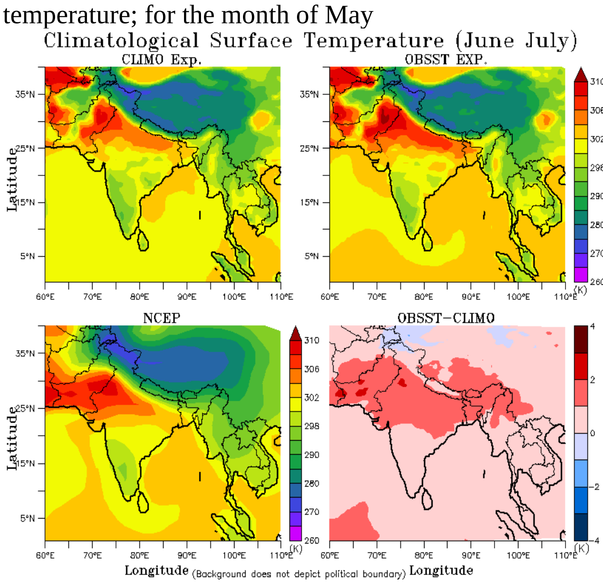

Figure 7: Long term onset monsoon climatology of surface temperature for the month of June-July

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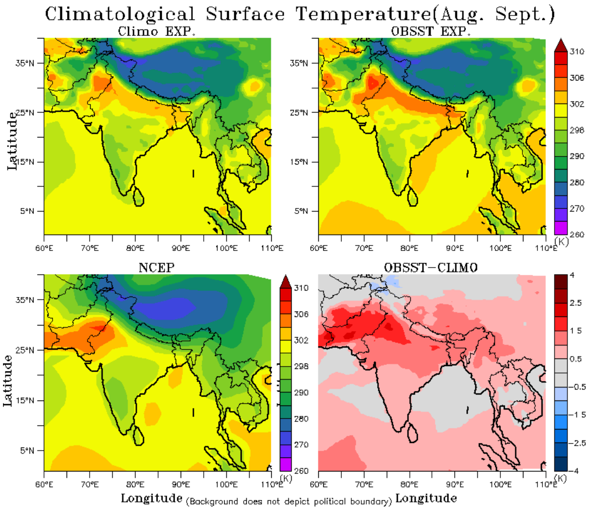

Figure 8: Long term monsoon climatology of surface temperature; for the month of August-September

During the months of August and September, the temperature of oceanic region is simulated by the OBSST Exp. but in case of inner-continental region OBSST Exp. has overestimated the temperature, instead CLIMO Exp. is near to capture towards the observed one. The surface temperature around the Himalayan region and its foot hills have been nicely reproduced by both the CAM climatology also able to capture well the surface temperature over the Mountainous region.

The monthly maximum, mean and minimum climatological surface temperature averaged over the study region simulated by CAM has been computed and validated with IPCC climatology. The comparison of the long-term average surface temperature along with the monthly maximum and minimum surface temperature simulated by CAM: CLIMO Exp. and OBSST Exp., with IPCC climatology has been presented in the figure 9 below.

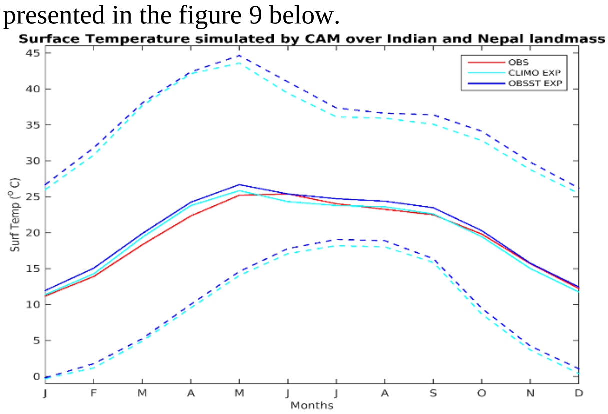

Figure 9: Comparison of mean, maximum and minimum monthly climatological surface temperature averaged over the Indian & Nepal landmass simulated by CAM (F05_g16) of CLIMO Exp., OBSST Exp. & observed (IPCC) surface climatology

The climatological surface temperature variation during the pre-monsoon and monsoon season simulated by both the experiments are having good amount of variation. The following figures 10 and 11 shows the temperature variation over the study region during pre-monsoon and monsoon season. The model simulated seasonal temperature over the region is able to pick the signal realistically to the observed one. So, it is inferred that the model is able to reproduce the anomaly of the temperature, which is the positive signal for being the model able to capture the inter-annual variation of the temperature.

4.2 Wind and Precipitation

Wind plays a major role in circulation of a system over the region. The wind is an indicator of weather. Wind circulation at different pressure levels play a major role in the climatic system over all the region round the globe.

The simulation of Indian Summer Monsoon rainfall does not depend only on the regional processes but largely influenced by several global phenomena as well as different regional tele-connections.

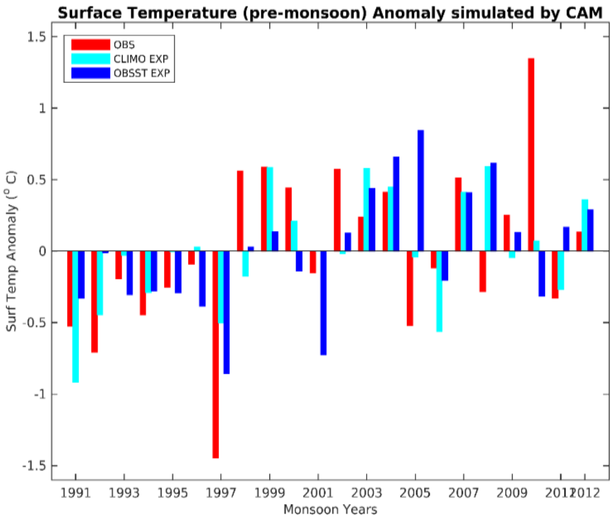

Figure 10: Annual variation of Temperature over the region of India & Nepal for the pre-monsoon month

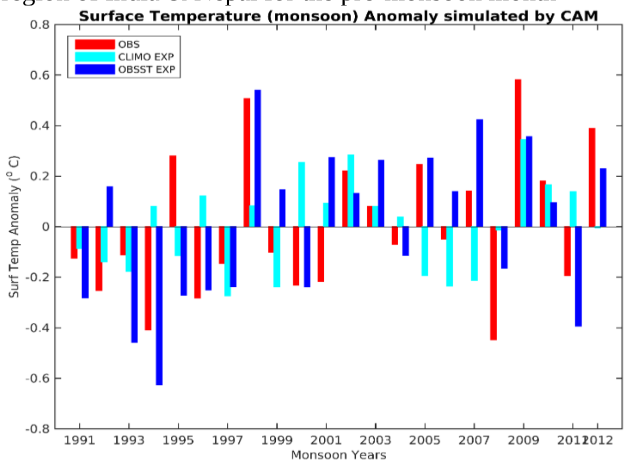

Figure 11: Annual variation of temperature over the region of India & Nepal for the monsoon months

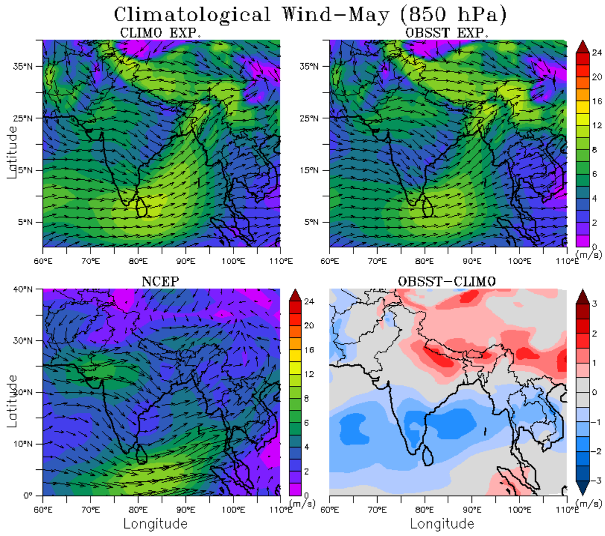

Figure 12: Long term wind climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month of May

It is necessary to analyze the climatology of wind circulation and rainfall simulated by CAM. The monthly climatology of wind circulation and rate of rainfall has been generated from both the long-term simulations of CAM and validated with the NCEP reanalysis generated wind climatology to ensure the realistic simulation of ISM.

When limiting oneself over the Extended Indian summer monsoon region, the rainfall is largely driven by atmospheric circulation of winds at various pressure levels with variation in time and space.

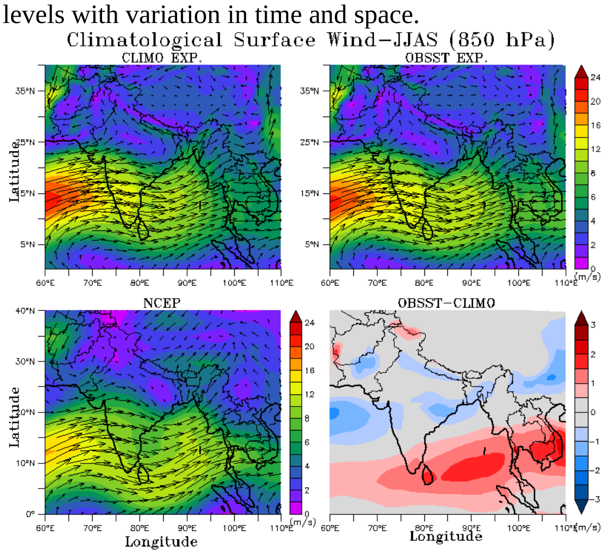

Figure 13: Long term wind 850 hPa climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month of June- September

The low-level westerly winds of 850 hPa are the driver to bring the moisture laden air from the Arabian Sea over the Indian sub-continent. The CAM climatology has captured the wind in the inner landmass of India whereas in the eastern coast, Bay of Bengal and in the southern part of India and SriLanka, it has overestimated the wind speed (pre-monsoon) as compared with the observed one. Similarly, in the mountainous region of Nepal also, the CAM climatology winds are overestimating the wind speed with observed one even though CLIMO Exp. is quite near to the observed climatology.

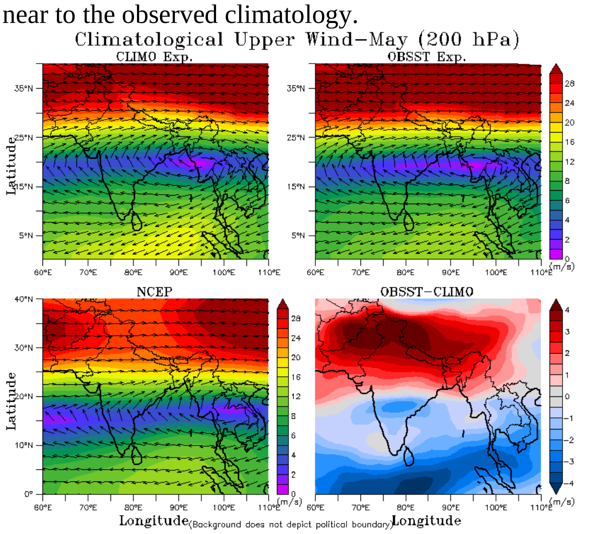

Figure 14: Long term wind 200 hPa climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month of May

During the time of monsoon, the strong passage of winds from Arabian Sea is clearly visible and is well simulated by the CAM climatology. The passage of 850 hPa monsoonal winds through southern part of India towards the Bay of Bengal, then becoming easterlies is even more clearly visible in CAM climatology. These low-level monsoon winds are carrying the abundant amount of moisture and pouring as rainfall in different part of sub-continents. These rain helps to decrease the intense heat of the inner-continental region as well as a good source for most of the people to start the cultivation of land. The anti-cyclonic circulation over the Tibetan landmass is weakly estimated in CAM climatology. The anti – cyclonic circulation over the Tibetan Plateau during the pre-monsoon season and monsoon season as seen in NCEP climatology has shifted further north in CAM simulated winds climatology in both the experiments.

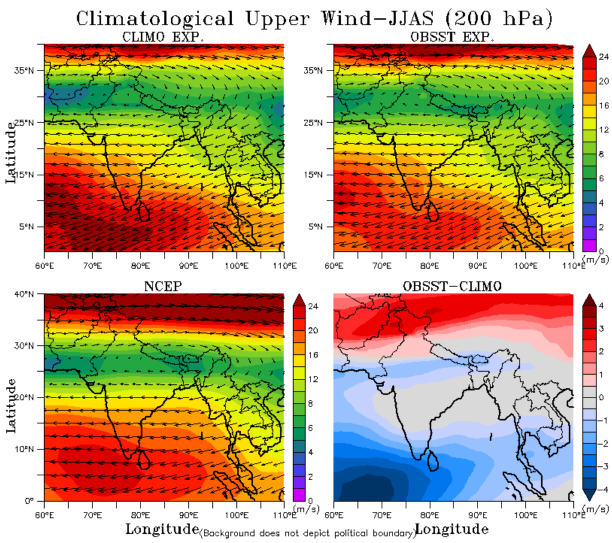

Figure 15: Long term wind 200 hPa climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month of June-September

Upper-tropospheric easterly winds near 200 hPa help steer weather systems that form over the Bay of Bengal westward across the Indian landmass. By providing favorable outflow and divergence aloft, these easterlies support and guide lower-level monsoon disturbances toward the interior, allowing the northern hills, mountain regions, and inner continental areas to receive substantial rainfall.

The model simulated climatological wind circulations at 200 hPa during the pre-monsoon (i.e. May), and monsoon (i.e. JJAS) have been compared with NCEP climatological winds. The above figure 14 and 15 shows the average wind at 200 hPa. Upper level winds during the period of May in CAM simulation over the region 24^0 N – 27^0 N has underestimated the wind speed by 2-3 m/s and in India the low wind speed in NCEP climatology extends from 15^0 N to 23^0 N but it has been concentrated in certain region i.e. 20^0 N to 25^0 N in the CAM climatology. During the period of monsoon, the upper winds are well simulated in both the simulations with overestimating the winds over The Arabian Sea in CLIMO Exp. than the OBSST Exp. and the observed one. However, the upper-level winds during monsoon season in the inner continental region is well simulated.

4.3 Bias Corrected Rainfall

New rainfall climatology has been generated of both the CAM experiments named CLIMO Exp. and OBSST Exp. after removing bias in monthly as well as in daily scale. Figure 16 shows the TRMM derived observed climatology for the months of June to September and mean seasonal scale rainfall over the study region. The model simulated climatology is affected by bias mainly over the regions of Western Ghats, Himalayan range, coastal region of Bay of Bengal and its surrounding regions. The model climatology has over-estimated the rainfall over these regions. So bias correction is done to correct the rainfall using GPCP rainfall climatology. The bias corrected model rainfall climatology shows reduced rain fall over the region, the maximum amount of rainfall over the Western Ghats, over the Himalayan range and even in inner central India are better represented by the bias correction.

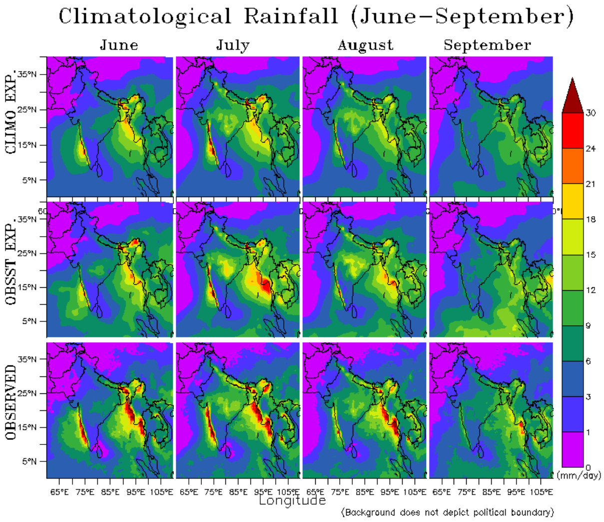

Figure 16: Long term monthly rainfall climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month through June-September

In comparison of both the simulations, the OBSST Exp. has over-estimated the rainfall over the regions of oceans, over east coast of Bay of Bengal, some inner part of India and foot hills of the Himalayas. The CLIM Exp. seems quite near to the observed one. The comparison of the model given long term output with the observed TRMM climatology gives the model capability of simulating the large-scale features of the Indian Summer Monsoon.

4.4 Inter-annual Variations of Extended ISMR

The annual variation of the Indian Monsoon Rainfall over the study region by the long-term simulation of 30 years i.e. 1991 to 2020 has been analyzed. The inter-annual variation is not very large, with the standard deviation being only about 8-10%. Figure 1.1.2 shows the annual variation of the seasonal anomaly of Extended Indian summer monsoon region. The result gives that the model simulated seasonal rainfall over the region is able to pick up the correct signal of positive or negative anomaly in most of the cases as compared to IMD observations also. From the figure, it can be revealed that all most both the experiments are able to reproduce the anomaly of the rainfall except in some cases. CLIMO Experiment and OBSST Experiment both are having the IAV of monsoon. CLIMO Exp. have some inter-annual variation but OBSST Exp. is somewhat close to capturing the realistic one. This gives positive signal that the climate models are also able to find the inter-annual variations.

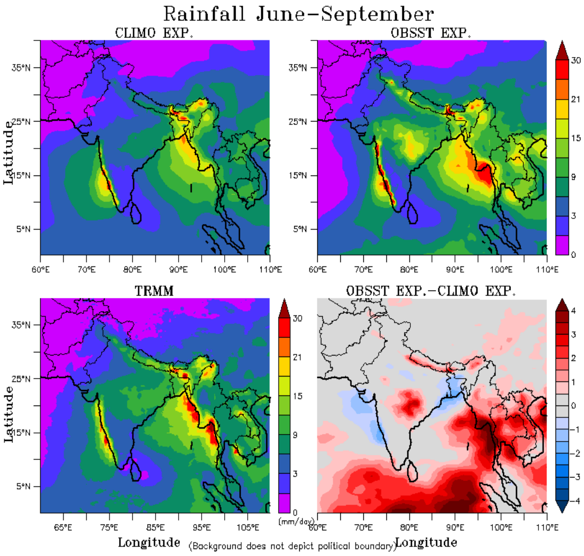

Figure 17: Long term monsoon seasonal climatology of CLIMO Exp., OBSST Exp., and Observed climatology for the month through June-September

4.5 Simulated Internal IAV of Indian summer monsoon

In the CLIMO experiment, the model is forced with climatological sea surface temperatures (SSTs) and thus experiences fixed lower-boundary conditions, so any interannual variability (IAV) of the monsoon that appears in this run arises purely from internal processes within the climate system, including feedbacks from interactive soil moisture (Goswami & Xavier, 2005). In contrast, the OBSST experiment prescribes observed monthly SSTs, so the simulated ISM in that run is influenced by both internal variability and externally imposed year-to-year SST changes. Comparing these two experiments allows us to test whether the model produces substantial monsoon IAV and whether the spatial pattern of the simulated variability resembles that seen in observations (Goswami & Xavier, 2005).

To quantify monsoon strength in both CLIMO and OBSST, two indices are constructed. The first is an extended All-India monsoon rainfall (AIR) index, defined as the June–September mean precipitation averaged over 70°E–110°E and 10°N–25°N, following the extended rainfall index proposed by Goswami and Krishnamurthy (1999). This regional index captures nonadiabatic heating associated with the ISM more effectively than the traditional index based solely on rainfall over the Indian landmass (Goswami & Krishnamurthy, 1999). The second index, KELLJ, measures the kinetic energy of the low-level jet, computed from June–September mean winds at 850 hPa averaged over 50°E–65°E and 5°N–15°N, where strong low-level southwesterlies from the Arabian Sea feed the monsoon circulation. Both AIR (defined as the JJAS precipitation anomaly over 70°E–110°E, 10°N–25°N) and KELLJ (the JJAS anomaly of 850-hPa wind kinetic energy over 50°E–65°E, 5°N–15°N) are calculated from the CLIMO and OBSST simulations. Aside from a few outlier years (e.g., 1991, 2010, 2011 in CLIMO and 1991, 1999, 2000, 2009 in OBSST), the two indices track each other closely, with an overall correlation of about 0.84 in both experiments, indicating that KELLJ is a robust dynamical proxy for the AIR-based rainfall variability (Goswami & Xavier, 2005).

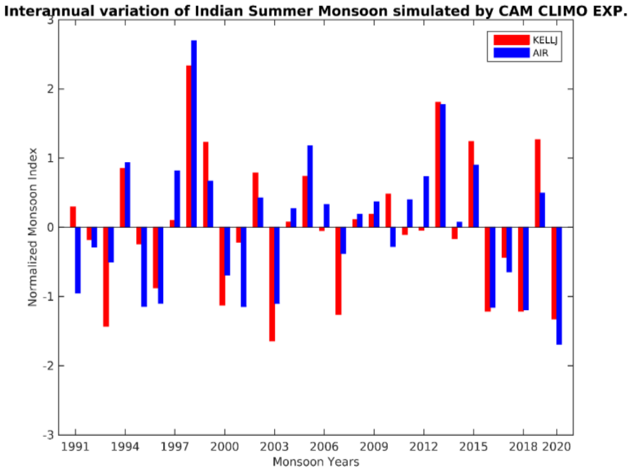

Figure 18: CLIMO Exp. simulated inter-annual variations of Indian Summer Monsoon

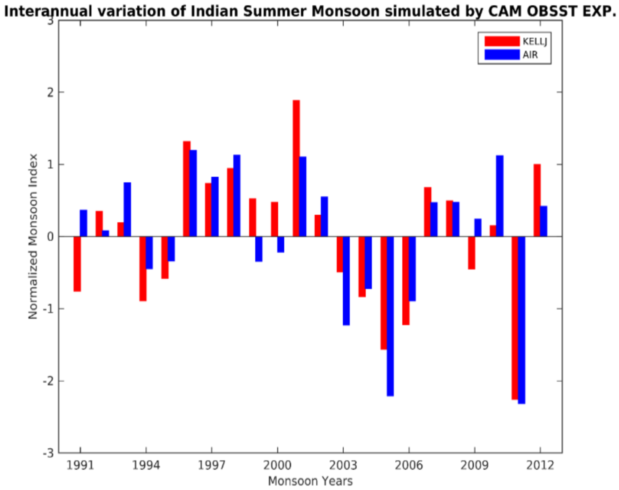

Figure 19: OBSST Exp. simulated inter-annual variations of Indian Summer Monsoon

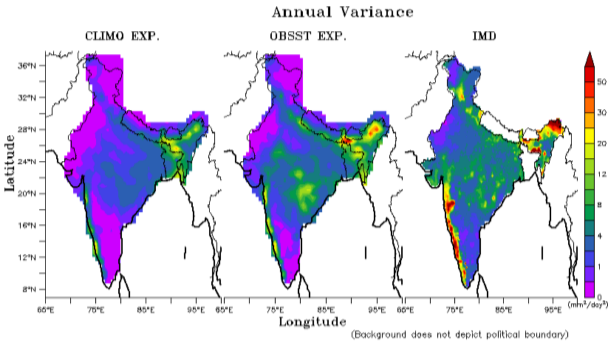

Figure 20: Inter-annual variance (mm^2/day^2) of seasonal mean precipitation from (a) CLIM, (b) OBSST and (c) IMD observations

Figure 20 shows the spatial variance structure of IAV of ISM over the land mass of the study region. The first

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experiment i.e. CLIMO Exp., shows a variation over the central Indian region, towards the northeast region, foothill of Himalayas and towards the Western Ghats. In OBSST Exp., the landmass has high variation of ISM. The model is able to pick the signals over the regions like; the foothills of Himalayas, the central Indian region, the eastern part of the subcontinent, the Western Ghats, even the northwestern part of the sub-continent. So, even in absence of inter-annually varying SST, the CLIMO Exp. well simulates the IAV of rainfall over the region. Over the landmass, CLIMO simulation has low variance, whereas OBSST simulation has yielded to capture IAV more realistically. So this model is simulating realistically with the observation.

4.6 Validation of In-situ Observations: A Case Study from Nepal

The validation of model forecasted rainfall and temperature (maximum and minimum) over Nepal landmass is carried out to demonstrate the model credentials as a separate case study. The in-situ observed daily data from DHM has been taken from 1991 to 2012 for this study. Several statistical tools have been used for the validation purpose. Scatter plot of all stations of Nepal minimum temperature, maximum temperature and rainfall has been plotted with collocated model data.

CAM simulated monthly average minimum and maximum surface temperature compared with in-situ minimum and maximum average surface temperature in a scatter diagram shows symmetrical distributions. CAM simulation (OBSST Exp.) is overestimating the monthly maximum as well as minimum surface temperature climatology.

CAM simulated monthly average rainfall compared with in-situ rainfall in a scatter diagram shows symmetrical distributions. Though CAM simulation (OBSST Exp.) is overestimating the monthly average rainfall it is quite close to observed in-situ rainfall climatology.

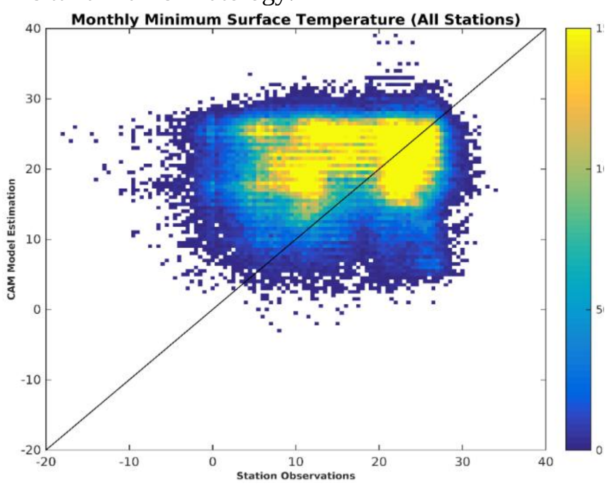

Figure 21: Scatter plot of CAM simulated (OBSST Exp.) and in-situ observed monthly minimum surface temperature of stations over Nepal

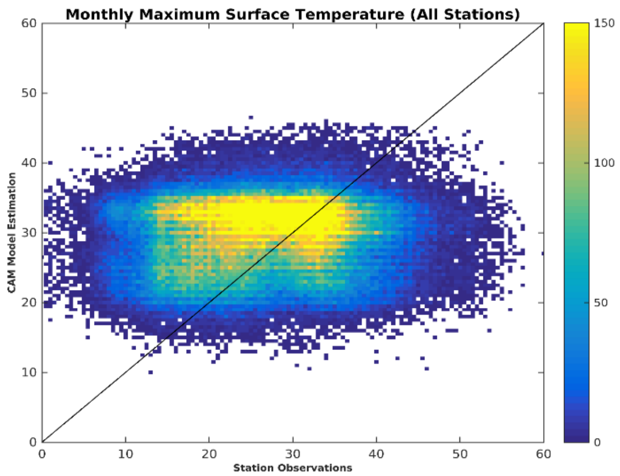

Figure 22: Scatter plot of CAM simulated (OBSST Exp.) and in-situ observed monthly maximum surface temperature over Nepal

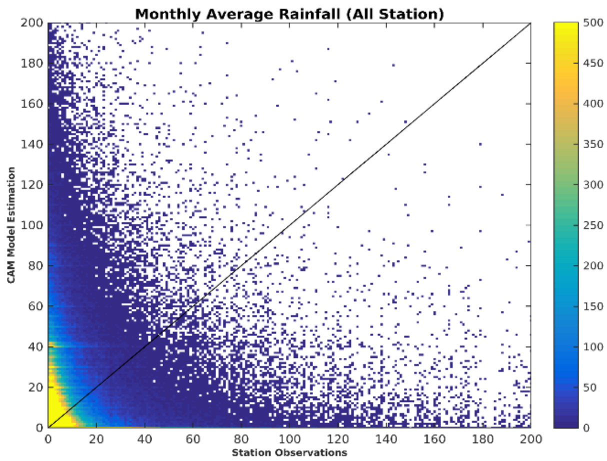

Figure 23: Scatter plot of CAM simulated (OBSST Exp.) and in-situ observed monthly average rainfall over Nepal

5. Conclusion

The long-term continuous model climatology has been generated by CAM model for the duration of 30 years and 22 years starting from 1991 with boundary condition of climatological SST for CLIMO Experiment and that of mid monthly OI-SST as OBSST Experiment. Analysis has been conducted for the pre-monsoon and monsoon seasons. The region of study is the extended Indian monsoon rainfall region i.e. 60° E – 110° E, 0° N – 40° N.

The monthly surface temperature climatology has been compared with NCEP reanalysis climatology for the spatial plot over the regions. The simulated surface temperature during pre-monsoon and monsoon are comparable with the observed values. The temperature over the oceanic region and the land mass are well matched. The heat lock originated west of India extends up to eastern coast and extends over the central India which is well simulated by both experiments but OBSST Exp. is realistic as the observed one and it vanishes during the monsoon season. The spatial distribution of temperature over the region is well captured. The temperature by the OBSST Exp. is overestimated to the CLIMO Experiment. The domain averaged surface temperature over the study region provides an insight that the model simulated temperature is well matched with observed temperature climatology. The annual variations of temperature anomaly simulated by CAM model (OBSST Exp.) is able to capture the good amount of variation as well as realistically to the observed one.

The wind circulation climatology at different pressure levels has been generated and analyzed with the NCEP reanalysis climatology. The wind circulation climatology simulated by the CAM model in both the experiments are realistic one. The monthly and seasonal (JJAS) wind climatology over the extended Indian monsoon region is able to capture the low-level jet of 850 hPa, the strong signature of 200 hPa easterly wind. Wind simulated by model in OBSST Exp. over the Arabian Sea towards inland of 850 hPa are close to the observed NCEP wind climatology whereas over the region and Tibetan plateau region it is underestimated in CLIMO Exp.

Analysis of bias corrected monthly rainfall over extended Indian monsoon region during the monsoon (JJAS) season revealed that a systematic seasonal pattern with the monsoonal rain-peak at July. The spatial distribution of the climatological monsoon rainfall shows variations over the landmass when compared with the TRMM climatology. The maximum rainfall over the regions of foothills of Himalayas, the Western Ghats are better represented by the bias-correction. The long-term continuous model simulations are able to capture the reasonable amount of inter-annual variations however, the extreme variations are not captured which is seen in observed climatology.

LLJ is strongly associated with monsoon rainfall. As the intensity of the kinetic energy increases, the stronger the LLJ; this implies more transport of water vapor in the Indian in-land that resulted to high rainfall during JJAS. Thus, there is a direct relationship between the two indices. The correlation is found to be 0.84 on both of the experiments.

Over the landmass, CLIMO Exp. has low variance, whereas OBSST simulation has yielded to capture IAV more realistically. So, this model is able to simulate realistically as compared with the observation.

Scattered plot of CAM simulated monthly average minimum and maximum surface temperature and rainfall when compared with DHM in-situ measurements shows the symmetrical distributions. CAM simulation (OBSST Exp.) is overestimating the monthly maximum as well as minimum surface temperature and also the rainfall climatology. Overall, the study is intended to find the inter-annual variation over the landmass using the CAM model and validate the in-situ observations.

Limitations:

The OI-SST experiment climate simulation is for the period up to 2012 only.

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