CLIMATE CHANGE STUDIES USING COUPLED MODEL—LAND SURFACE PERSPECTIVE

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ABSTRACT:

Climate involves a complex interplay of physical, chemical and biological processes of the atmosphere, ocean, sea-ice and land surface. It is now well understood that although detailed weather fluctuations can not be predicted beyond a certain time period, it is possible to predict several space-time averaged processes of atmosphere, land, ocean and sea-ice over a certain regions for a longer period of time i.e. climate change. This has been made possible because of better understanding of the dynamics of the coupled tropical ocean-atmosphere system and also significant improvements have been made in the models of atmosphere and oceans. A major component of any climate model is the representation of Land Surface Processes. The land surface exchanges moisture, momentum and heat with atmosphere. More realistic treatment of land parameters like soil wetness, land use and land cover changes including urbanization, Leaf Area Index (LAI) etc. are required to be done adequately. The land surface processes (LSP) are significant because of their heterogeneous nature - spatially and temporally. A successful inclusion of LSP in climate model must address the issues related to the regional scale variation of the properties of LSP. This is why a proper understanding of land surface processes is very crucial for climate simulation using numerical models. Community Climate System Model (CCSM3), a coupled model developed at National Center for Atmospheric Research (NCAR) containing atmosphere, ocean, sea-ice and land processes, simulation have been analysed for suitability in the Indian Monsoon region. The offline Community Land Model (CLM), taken from CCSM3, simulation forced with a given atmospheric conditions have also been analysed for the Indian Monsoon region. Both the simulation results are compared with observed climatological features and assessment to improve CCSM3 for regional climate change studies is made.

1. INTRODUCTION

Climate involves a complex interplay of physical, chemical and biological processes of the atmosphere, ocean, sea-ice and land surface. It is understood that weather fluctuations can not be predicted beyond a certain time, however, it is possible to predict several space-time averaged phenomena of atmosphere, land, ocean and sea-ice over a specific region for a longer period of time i.e. climate change. This has been made possible because of proper understanding of the dynamics of the coupled tropical ocean-atmosphere system and also significant improvements have been made in the models of atmosphere and oceans. The proper understanding of Land Surface Processes is one of major component of any climate system because of their heterogeneous nature - spatially and temporally. The land surface processes exchanges moisture, momentum and heat with atmosphere. The more realistic representation of land processes like soil wetness, land use and land cover changes including urbanization, Leaf Area Index (LAI) etc. are required to be addressed. To understand the changing procedure of the climate and to foretell the true future climate/weather, the research community feels the necessity of a climate system model coupled with atmosphere, ocean, land surface and sea-ice in an interactive mode. As a result, the Community Climate System Model (CCSM) has been procreated from the Community Climate Model (CCM), a global atmospheric model, and made available to the users worldwide by the climate research community to represent the principal components of the climate system and their interactions. The CCSM is a coupled model for simulating past, present, and future climates. In its present form, CCSM consists of four components for the atmosphere, ocean, sea-ice, and land surface linked through a coupler that exchanges fluxes and state information among these components. CCSM3 is the CCSM version 3 model and, is used for the present study. In this study, a climate simulation of CCSM3 model and one year offline simulation of Community Land Model (CLM) have been compared. The short description of different component of CCSM3 is given in section 2. The section 3 describes the results and discussion from the simulation study, while conclusions are given in section 4.

2. OVERVIEW OF CCSM3

The CCSM3 system includes new versions of all the component models: the Community Atmosphere Model version 3 (CAM3; Collins et al. 2006), the Community Land Surface Model version 3 (CLM3; Dickinson et al. 2006), the Community Sea Ice Model version 5 (CSIM5; Briegleb et al. 2004), and the ocean is based upon the Parallel Ocean Program version 1.4.3 (POP; Smith and Gent 2002). New features in each of these components are described below. Each component is designed to conserve energy, mass, total water, and freshwater in concert with the other components. CCSM3 has been designed to produce simulations with reasonable fidelity over a wide range of resolutions and with a variety of atmospheric dynamical frameworks. This is accomplished by introducing dependence on resolution and dynamics in the time step and 12 other adjustable parameters in CAM3 (Collins et al. 2006). The standard version of CAM3 is based upon the Eulerian spectral dynamical core with triangular spectral truncation at 31, 42, and 85 wave-numbers. The zonal resolution at the equator ranges from 3.75° to 1.41° for the T31 and T85 configurations. The vertical dimension is treated using 26 levels with a hybrid terrain-following coordinate. The vertical grid transitions from a pure sigma region in the lowest layer through a hybrid sigma–pressure region to a pure pressure region above approximately 83 mb. The physics of cloud and precipitation processes include separate prognostic treatments of liquid and ice condensate; advection, detrainment, and sedimentation of cloud condensate; and separate treatments of frozen and liquid precipitation (Boville et al. 2006). The radiation is based on generalized treatment of cloud geometrical overlap (Collins et al. 2001) and the parameterizations for the long-wave and shortwave is interactive with water vapor. The land model is integrated on the same horizontal grid as the atmosphere, although each grid box is further divided into a hierarchy of land units, soil columns, and plant functional types (Dickinson et al. 2006). There are 10 subsurface soil layers in CLM3. Land units represent the largest spatial patterns of sub-grid heterogeneity and include glaciers, lakes, wetlands, urban areas, and vegetated regions. The turbulent transfer coefficient dependent on canopy density characterized by leaf and stem area indices (Dickinson et al. 2006). The transfer coefficient is used to obtain aerodynamic resistances for heat and moisture that are inputs to the calculations for latent and sensible heat fluxes. Over large areas of Eurasia, these changes result in a reduction in the 2-m air temperature by 1.5–2 K. The different surface data for each land grid cell are glacier, lake, wetland, and urban portions of the grid cell; the fractional cover of the 4 most abundant PFTs in the vegetated portion of the grid cell; monthly leaf and stem area index and canopy top and bottom heights for each PFT; soil color; and soil texture. These fields are taken from International Geosphere-Biosphere Programme (IGBP) land-surface datasets and interpolated to model grid from high resolution data sets. The atmospheric forcing parameters (viz. wind, temperature, humidity, precipitation and solar radiation etc) required to integrate offline CLM3 are provided from NCEP analysis. The ocean model uses a dipole grid with a nominal horizontal resolution of 3° or 1°. The semi-analytic grids have the first pole located at the true South Pole and the second pole located over Greenland. The vertical dimension is treated using a depth (*z*) coordinate with 25 levels extending to 4.75 km in the 3° version and 40 levels extending to 5.37 km in the 1° version. The 1° grid has 320 zonal points and 384 meridional points. The spacing of the grid points is 1.125° in the zonal direction and roughly 0.5° in the meridional direction with higher resolution near the equator. The sea ice model is integrated on the same horizontal grid as the ocean model. The physical component models of CCSM3 communicate through the coupler (Drake et al. 2005). The physical models execute and communicate via the coupler in a completely asynchronous manner. The coupler links the components by providing flux boundary conditions and, where necessary, physical state information to each model. The coupler monitors and enforces flux conservation for all fluxes that it exchanges among the components. The basic state information exchanged by the coupler includes temperature, salinity, velocity, pressure, humidity, and air density at the model interfaces. The basic fluxes include fluxes of momentum, water, heat, and salt across the model interfaces. The three standard configurations of CCSM combine the T31 CAM/CLM with the 3° POP/CSIM, the T42 CAM/CLM with the 1° POP/CSIM, and the T85 CAM/CLM with the 1° POP/CSIM. For the present study T42 CAM/CLM with the 1° POP/CSIM is employed due to constrain in computational power. However, in future scientific study with finer resolution will be carried out.

3. RESULTS AND DISCUSSIONS

A climatological simulation of CCSM3 and one year offline simulation CLM3 has been accomplished. The climatological simulation is accomplished using the default setting of all the parameters for all the model components. The output parameters are stored as monthly mean. Since our interest is only related to atmospheric processes, we analyzed few parameters from the atmospheric and land component of the model only. The offline land model results are also analyzed. The parameters analysed in this study are simulated climatological large-scale circulation features, surface latent and sensible heat fluxes, surface temperature and precipitation rate both from the coupled and offline simulations. The NCEP climatological analysis is used to verify the temperature, large-scale circulation and fluxes, while the GPCP climatological rainfall analysis is used to verify the simulated precipitation rate.

The simulated climatological large-scale circulation features for the month of June-July-August (JJA) and the corresponding climatological circulation features from the NCEP analysis are shown in Fig. 1(a-b). The cross-equatorial flow, the Somali jet and the dominant features of the monsoon circulation over Arabian Sea have been reproduced satisfactorily in the simulations (Fig. 1a). The strength of the Somali jet is around 12-14 m/s in the NCEP analysis (Fig. 1b); however, in the simulation it is around 8-10 m/s. The west coast of India and west coast of Southeast Asia experience strong onshore flow near 0^oN to 15^oN. Though the model has been able to simulate the large-scale circulation features quite well, it has underestimated the strength of flow in most of the high wind region especially near Somali region, Southern Indian Ocean and Southern Pacific Ocean. The meridional component of the wind is also simulated satisfactorily. The gyre like flow present in the Northern Pacific Ocean in the NCEP analysis is absent in the simulation. Figure 1(c-d) shows the simulated climatological large-scale circulation features for the month of December-January-February (DJF) and the corresponding climatological circulation features from the NCEP analysis. The NCEP date (Fig. 1d) shows easterlies over the Indian monsoon region and south of Indian Ocean i.e. south of 10^oS, with very weak westerlies in between equator and 10^oS, with very weak westerlies in between equator and 10^oS. The simulation (Fig. 1c) shows easterlies over south and westerlies over north of Indian monsoon region with comparable magnitudes as in observations. The strength of the easterlies over the Indian monsoon region is slightly stronger as compared to the observed in the simulations. However, the weak easterlies along 5^{o}S are simulated like in the observations. The dominant flow along equatorial region, Southern Indian Ocean is underestimated in the simulation. As a whole, the flows in the simulation are underestimated both in the summer and winter seasons.

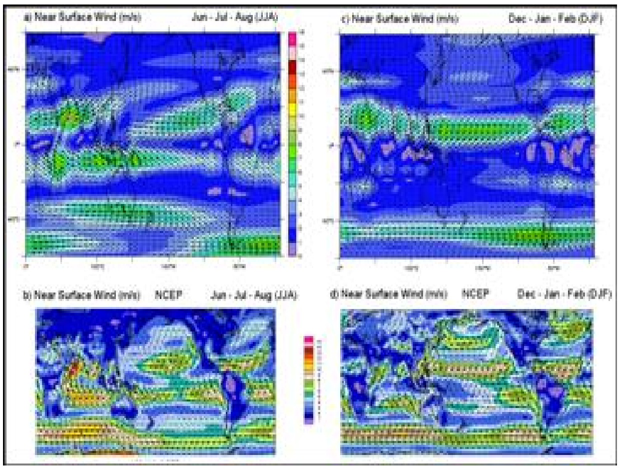

Figure 1. (a-b): The Mean Climatological Simulated June-July-August (JJA) Near Surface Wind (m/s) and the Corresponding JJA Winds from the NCEP. (c-d): Same as (a-b) but for December-January-Feb

The rainfall, the most important parameters for the tropical weather system is discussed here. The June-July-August (JJA) climatological precipitation rate from the simulation and the corresponding GPCP rain rate are shown in Fig. 2(a-b). The GPCP JJA mean rain rate (Fig 2b) over India shows two peaks: a relatively weaker one over Western Ghats and another, a relatively stronger peak, over the head of the Bay of Bengal. Both of these areas receive strong onshore flow. The rain rate produced in simulation is of higher magnitude in comparison to the GPCP magnitudes over most parts of India. However, the orientation of the strong rainfall belt matches well with the observation, which extends from India eastwards and shows southwards tilt. The simulation has produced a very high unrealistic rainfall over central African region, which is not present in the GPCP rain rate. The mean climatological December-January-February (DJF) precipitation rate from the simulation and corresponding GPCP rain rate are shown in Fig. 2(c-d). The GPCP rain rate (Fig. 2d) is homogeneously distributed over the whole Indian Ocean, with two peaks: one over Madagascar and another over southwest Asia. Though the simulation has also produced the two peaks, the magnitude of rain rate peaks in the simulation is over estimated. The simulation has produced a very unrealistic high rain over equatorial Pacific Ocean, which is not present in the GPCP rain rate. The monthly averaged time-series of simulated rainfall (mm/day) from the CAM (Fig-3a) and the CLM (Fig-3b) along with observation in the coupled as well as offline simulations over Indian sub-continent are shown in Fig. 3. The coupled simulation has underestimated rainfall in both the figures, while offline simulation result of CLM matches quite well with the observation.

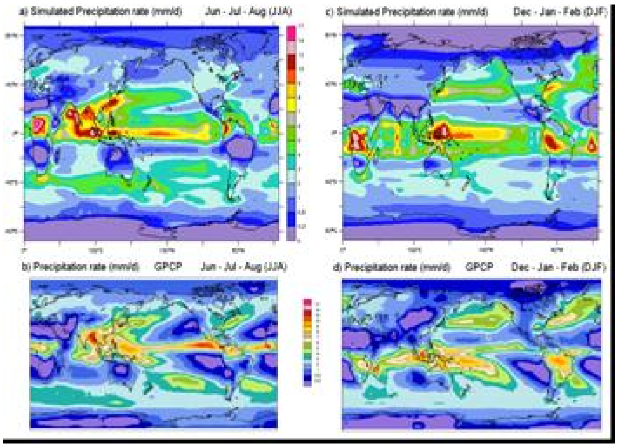

Figure 2. (a-b): The Mean Climatological Simulated June-July-August (JJA) Precipitation Rate (mm/d) and the Corresponding JJA Precipitation Rate from GPCP. (c-d): Same as (a-b) but for December-January-February (DJF)

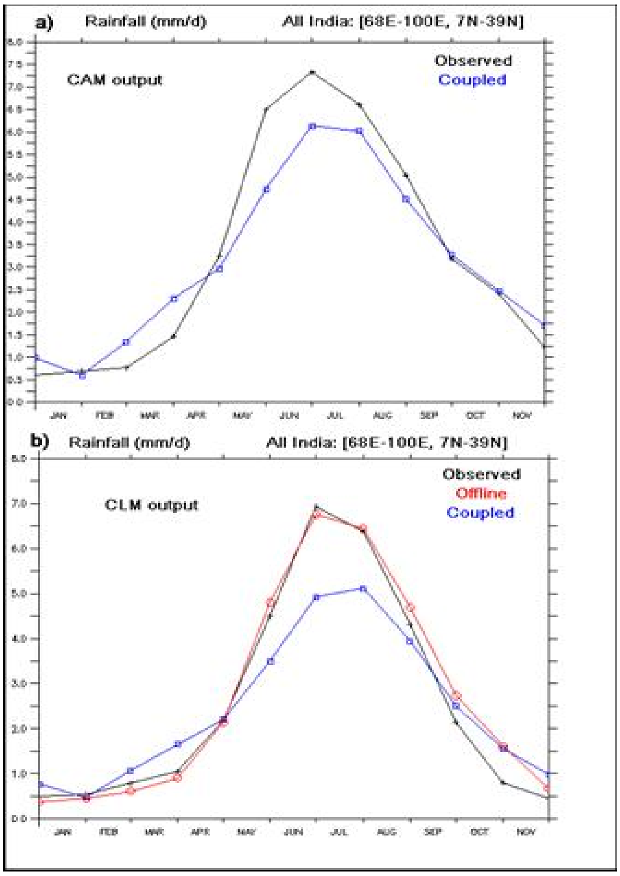

Figure 3. a) Time-series of Simulated Rainfall (Community Atmospheric Model - Coupled Simulation) along with Observation. b) Time-Series of Simulated Rainfall (Community Land Model – Coupled and Offline Simulation) along with Observation. (Over Indian region)

The projection of surface temperature is another crucial parameter for climate change studies. The simulated mean climatological

June-July-August (JJA) surface temperature and corresponding climatological surface temperature from the NCEP analysis are shown in Fig. 4(a-b). The isotherms in the NCEP analysis (Fig. 4b) are distributed well in the Indian Ocean region, with maximum temperature is ranging in between 300-305 K. The spatial pattern of the simulated surface temperature is also matches well with the observed temperature. However, in the simulation, range of maximum temperature contour is higher by 3-4 degree when compared with that of observed one. This could be due to improper surface flux correction between ocean and atmospheric model. The simulated mean climatological December-January-February (DJF) surface temperature and corresponding mean climatological DJF surface temperature from NCEP analysis are shown in Fig. 4(c-d). The simulated surface temperature structure is matches well with observed features. However, range of maximum temperature contour is higher by 3-4 degree in the simulation when compared with observed temperature. Overall there is higher temperature contours are present in the simulation when compared with NCEP analysis. The monthly averaged time-series of simulated surface temperature (K) from the CLM along with observation in the coupled as well as offline simulations over Indian sub-continent are shown in Fig. 5. The coupled simulation has overestimated surface temperature by about 8-10K, while offline simulation result of CLM has also overestimated the temperature by about 3-5K when compared with observation. The high overestimation in the coupled simulation may be due to the improper surface flux correction during coupling between ocean and atmospheric model.

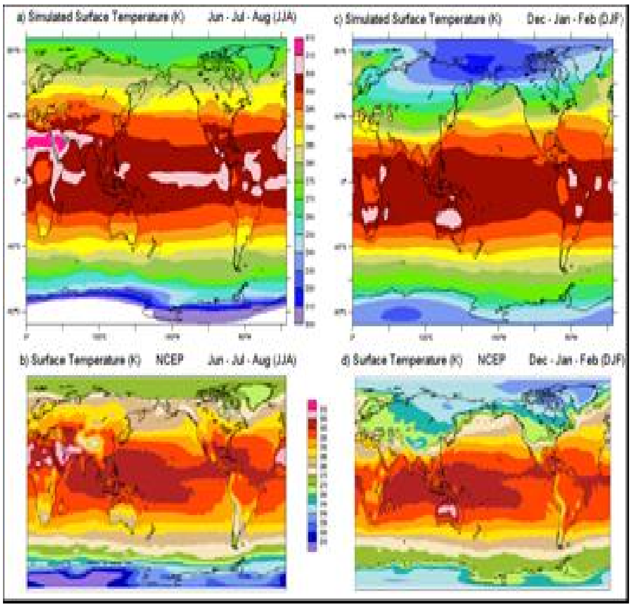

Figure 4. (a-b): The Mean Climatological Simulated June-July-August (JJA) Surface Temperature (K) and the Corresponding JJA Surface Temperature from NCEP. (c-d): Same as (a-b) but for December-January-February (DJF)

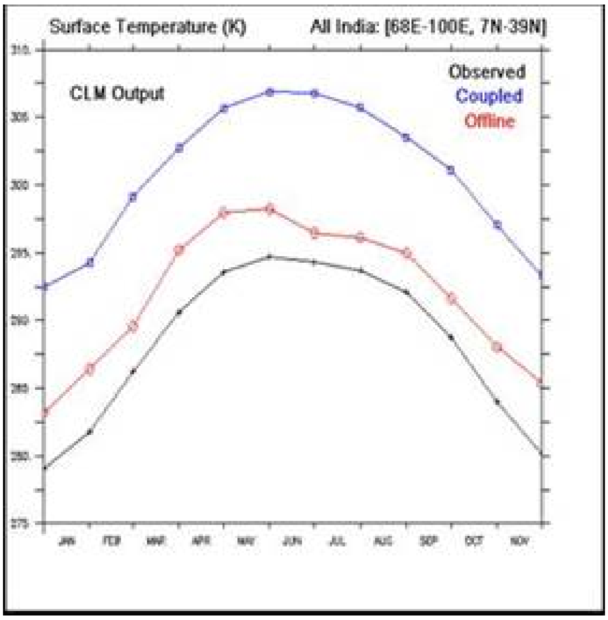

Figure 5. Time-series of Simulated Surface Temperature (Community land model - Coupled and Offline Simulations) along with Observation

The deficiency in the understanding of ocean and cloud processes in the global climate system can lead to wrong climate prediction. Heat transfer at the sea surface plays a crucial role to link the ocean and the atmosphere, and consequently, to the generation of clouds. Therefore, monitoring of the heat transfer between the ocean and the atmosphere is crucial for understanding a global climate system. The heat transfer has four components, that is, shortwave radiation, long-wave radiation, latent heat flux, and sensible heat flux. Shortwave radiation transfers heat from the atmosphere to the ocean, while the other three components mainly transfer heat from the ocean to the atmosphere. The magnitude of the heat flux strongly depends on time and location. Generally, shortwave radiation and latent heat flux are principal components of the heat transfer. Although the shortwave radiation is larger than latent heat flux, the latent heat flux is more important for the global climate problem because of inherent characteristics, like the large amplitude of inter-annual and spatial variability. It is in striking contrast to shortwave radiation. The shortwave radiation has large diurnal and annual distribution pattern over different locations. This variability is depends on the representation of atmospheric constituents (e.g. aerosol parameters), their representative values, cloud types and attenuation. All these require region specific calibration with in situ measurements. The latent heat included in water vapor can be freely moved from one place to another. This characteristic is closely related to the redistribution of heat energy in the global climate system and is one of the essential factors for understanding a global climate system. Numerical Weather Prediction (NWP) analysis-forecast systems provide 6-hourly fluxes with global coverage. However, uncertainties in model physical parameterizations can lead to uncertainties in surface fluxes from the global NWP analysis-forecast systems. Differences in model and data assimilation configurations also lead to discrepancies in surface fluxes between different analysis products.

The simulated climatological surface latent heat flux for the month of June-July-August (JJA), December-January-February (DJF) and the corresponding climatological latent heat flux from NCEP analysis are shown in Fig. 6. The model has been able to simulate the observed features quite well during JJA as well as DJF over the Pacific Ocean and south Indian Ocean. However, the model has underestimated the latent heat flux over Atlantic Ocean and Central America. Sensible heat flux at the air-sea interface is due to the temperature difference between the cold skin and air temperatures. A falling raindrop is in thermal equilibrium with its surroundings, with a temperature corresponding to the web-bulb temperature of the atmosphere at its height. The temperature of the raindrop as it hits the ocean surface is equivalent to the web-bulb temperature of the atmosphere just above the surface. The differences between these two temperatures could range from small to larger depending on the nature of the rain. Both latent and sensible heat fluxes are important parameters in understanding the atmosphere/ ocean heat and fresh water transports.

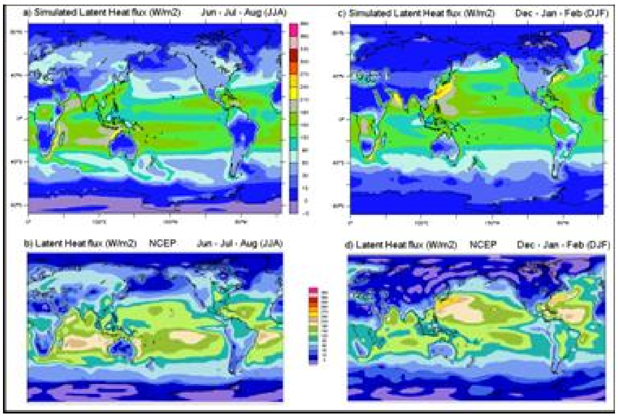

Figure 6. (a-b): The Mean Climatological Simulated June-July-August (JJA) Surface Latent Heat Flux (w/m^2) and the Corresponding JJA Surface Latent Heat Flux from NCEP. (c-d): Same as (a-b) but for December-January-February (DJF)

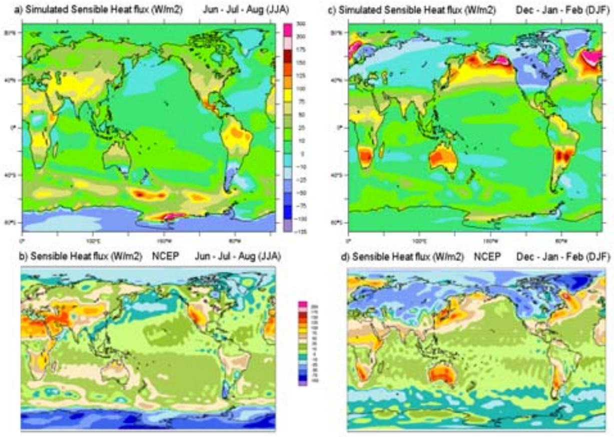

Figure 7. (a-b): The Mean Climatological Simulated June-July-August (JJA) Surface Sensible Heat Flux (w/m^2) and the Corresponding JJA Surface Sensible Heat Flux from NCEP. (c-d): Same as (a-b) but for December-January-February (DJF)

The simulated mean climatological June-July-August (JJA) surface sensible heat fluxes and corresponding mean climatological JJA surface sensible heat fluxes from the NCEP analysis are shown in Fig. 7(a-b). The pattern of fluxes in the simulation (Fig. 7a) has matches closely with observation (Fig. 7b), however the model has under estimated the fluxes over Pakistan and Afghanistan. The simulated mean climatological December-January-February (DJF) surface sensible heat fluxes and the corresponding mean climatological DJF surface sensible heat fluxes from the NCEP analysis are shown in Fig. 7(c-d). The simulated fluxes from the CCSM model matches quite well with the observed fluxes. The monthly averaged time-series of simulated latent heat-flux (Fig. 8a) and sensible heat-flux (Fig. 8b) from CAM along with observation from the coupled simulations over Indian subcontinent are shown in Fig. 8. The pattern of annual cycle of simulated latent heat-flux matches quite well with observation, however, there some differences with range a range of 8-10 w/m^2 in the exact value of fluxes over Indian subcontinent region. The pattern of annual cycle of sensible heat-flux has also matched quite well with the observation. However, the coupled simulation has overestimated the sensible heat-flux over Indian subcontinent.

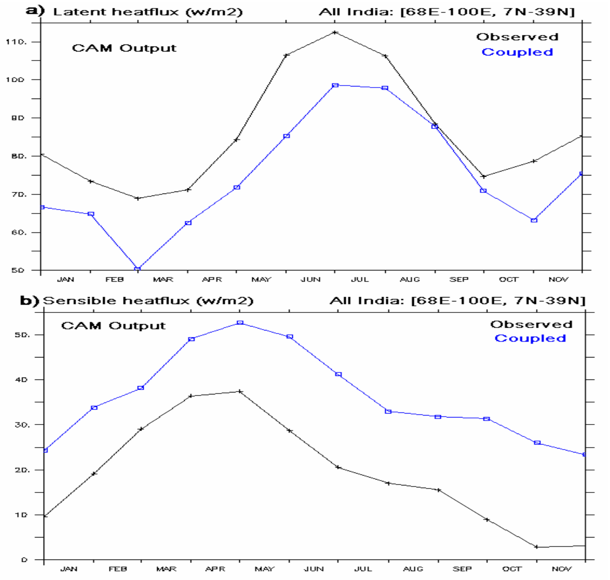

Figure 8. a) Time-series of Simulated Latent Heat-Flux (Community Atmospheric Model) and b) Time-series of Simulated Sensible Heat-Flux (Community Atmospheric Model) along with Observation Over Indian Region

CONCLUSION

A 10-year climatological branch run of CCSM3 has been done using the restart files from NCAR's 1990 control run as initial conditions with the default setting of all the model components and one year offline simulation CLM3 has been accomplished. All the model outputs are stored on mean monthly basis. The preliminary results of the simulation of atmospheric components like large-scale circulation, surface temperature, rainfall, latent and sensible heat fluxes are analysed and compared with observed climatological features. The rainfall simulation from the CLM for coupled as well as offline simulations are compared. The parameters from the offline simulation of CLM3 match reasonably well with observations than the coupled simulation results. The other simulation results are comparable with the observed features with a few exceptions in the simulation of surface temperature and fluxes in the coupled simulation. The major differences in the coupled simulation may be due to the overshooting of sea-surface temperature because of high biases generated during coupling of Ocean and atmosphere. These deficiencies will be addressed in future studies using real-time forcing the coupled simulation.

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