Prediction of monsoon using a seamless coupled modelling system

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Rainfall for India and South Asian region mainly comes during the summer monsoon period. Realistic model representation of monsoon rainfall variability is a scientific challenge and is of great societal consequences. Due to scale interactions, study of monsoon variability and predictability from hours to a season using a realistic model is of vital importance. Under the Ministry of Earth Sciences, National Monsoon Mission, National Centre for Medium Range Weather Forecasting (NCMRWF) is focusing on the week-2 forecast of monsoon rainfall using a coupled model and its initialization. Improving the skill of models within the timescale of the first two weeks period is vital because of its seamless connection to the monsoon intraseasonal and seasonal variability and prediction. Model development for monsoon rainfall has to be dealt in a holistic way, including the scales from days to a season. NCMRWF on its effort to undertake advanced research in tropical/monsoon simulation/prediction across a range of timescales from hours to a season, has made one incremental step forward by implementing a state-of-the-art coupled model. In this study, we report results from monsoon simulations from the high-resolution global assimilation–forecast set-up in NWP medium range timescale and also from the simulation results from a relatively coarser coupled model. The monsoon lower tropospheric flow and associated rainfall patterns are quite realistic. The existing model biases in flow, rainfall and surface parameters are also discussed. To remain at the forefront of monsoon prediction, a much higher resolution version of the coupled model and its initialization component will be implemented in the coming years on a more powerful supercomputer. The focus will be to improve simulation of coupled monsoon variability in timescale of hours to a season with an aim to improve forecast skill in week-2 time-period over the Indian region.

Keywords: Coupled model, data assimilation, monsoon modelling, rainfall variability.

Introduction

Weather and climate of the South Asian summer monsoon region are a complex coupled atmosphere–ocean–land–ice interactive phenomenon. To understand and predict the monsoon and tropical weather systems, better numerical simulation models and data assimilation systems have been developed by leading modelling centres. However, simulation of Indian summer monsoon variability at various space and timescales by numerical modelling is a challenging task as the model skill is lagging behind those for the mid-latitude weather systems. In tropical regions, due to slowly varying boundary ocean/land conditions, potentially it is possible to simulate/predict the variability beyond days up to a season1. However, current models have biases for monsoon/tropics, which probably are limiting the skill of rainfall prediction beyond a few days. For India and many neighbouring countries of South Asia, the monsoon rainfall variability has strong socio-economic consequences. Therefore, there is an urgent requirement of improved understanding of the interconnections between the Indian regional monsoon rainfall variability and other modes of weather/climate variability through enhanced observations and modelling activities2. Recently, studies suggest that human activities through industrialization and increased population have started affecting the weather/climate regimes through anthropogenic warming and are a cause of global concern. Due to existing uncertainties in model simulations of monsoon at shorter scales of days to a season, it is not possible to use present-day models with confidence to assess the future projections related to monsoon climate change. Seeing the challenges and utility of monsoon modelling, Ministry of Earth Sciences (MoES), New Delhi has launched the ‘National Monsoon Mission’ project during its XII Plan period to boost monsoon research in an accelerated manner by collaborating with multiple international agencies and the world scientific community3.

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The whole issue of modelling the complex monsoon system from hours to a season has to be dealt with as a single entity. The evolution of weather and climate is linked by the same physical processes in the atmosphere–ocean–land–cryosphere system operating across multiple space and timescales. It is well documented that the model biases seen at extended range (month to a season) are in fact generated within the first few days of model integration and complex feedback processes. For monsoon the errors develop within the medium-range timescale itself, and it is more serious when the monsoon is either in active or break state. Therefore, from model development viewpoint, it is better to use the same model across a range of temporal and spatial scales. The benefit of using a seamless prediction system across a wide range of scales is highly recommended. The World Climate Research Programme’s (WCRP’s) world modelling summit in 2008 also adopted the notion of weather and climate as a seamless problem from model development angle. In a recent review article, the practical experiences at UKMO in seamless prediction approach was summarized indicating real benefit for further model developments. Moving ahead with the seamless approach for monsoon forecasts is the right direction in bridging the gap between weather and climate research.

In spite of all the latest developments in modelling and data assimilation, the skill of medium range rainfall forecast for large-scale monsoon is only up to day three to five. Even state-of-the-art global models show large errors for longer lead times, which could be related to unrealistic representation of diurnal cycle of monsoon rain over land and ocean. The limiting skill of medium-range monsoon rainfall forecasts for the India (South Asia) region could be related to the lack of model capability to capture the processes of the coupled monsoon system fully resolving the range of scale-interactions. Other things such as poor ocean–atmosphere coupling, missing processes, poor model resolution, etc. could equally play a role. It has been documented that during active phase of MJO, the medium-range forecast skill drops further due to lack of proper representation of the dominant convective variability in the atmosphere-only model. The background MJO scale needs to be resolved in the medium-range forecast model. Study of features related to intraseasonal oscillations of tropics and monsoons are important to understand, simulate and predict the dynamical and physical processes related to tropical South Asian monsoons. To better represent the air–sea interaction, we have to consider the ocean thermo-haline circulation and large-scale changes in ocean heat content to interact with the atmosphere. Additionally realistic representation of evolution of El Niño and Indian Ocean Dipole is required for monsoon modulation. For tropical weather systems, there is a requirement of using coupled models.

All these studies point towards the use of coupled ocean–atmosphere model for resolving monsoon/tropics even in medium range and up to a season in a seamless manner. From Atmospheric Model Inter-Comparison Project (AMIP) model diagnostic studies and subsequent use of coupled models, it is clear that for monsoon simulation beyond medium range (monthly/seasonal), atmosphere-only models cannot be used. Coarse-resolution coupled models (used in AR4) also cannot simulate the nonlinear SST–rainfall relationship. However, recent studies with high-resolution coupled models are providing enough hints on the degree of sophistication we need for monsoon prediction. Current coupled models can potentially produce skillful prediction of Indian summer monsoon rainfall and its interannual variability. The role of coupled processes to capture MJO over the Indian and Pacific Ocean regions in model simulations has been studied extensively. Improved representation of the diurnal cycle coming from an increased upper ocean vertical resolution is a key factor in improved MJO skill. There are other important studies suggesting improvement of intraseasonal variability in the model due to coupling. Due to better representation of the Intra-seasonal Variability (ISV) in coupled models, NCEP is planning to use its latest coupled model CFSV2 for its forecasts up to week-6 having several ensemble members. ECMWF has very high-resolution coupled model for its monthly forecasts, which can capture the ISV better than the atmosphere only model. In fact current operational coupled models can capture the summer intraseasonal oscillations and their northward propagation with some skill, 1–3 weeks in advance. Latest coupled medium-range experiment studies at UK Met Office (UKMO) with a high resolution coupled model also suggest tropical skill improvement over the atmosphere only model. These coupled models should have the capability to take care of the natural variability of the earth system, including the externally forced changes. In this context realistic representation of current anthropogenic source of greenhouse gases, aerosol concentrations (including volcanic) and solar irradiance are important parameters to be taken care of in the seamless model to be used from days to a season.

Many recent studies show that the representation of seasonal monsoon rainfall in coupled models is improving gradually as the models become more sophisticated in terms of resolution and physics. For example, the EU ENSEMBLES models were better than the DEMETER models. Current operational models from lead centres have further improved. The predictive nature of the seasonal monsoon through its teleconnection with ENSO can be captured well by improving the mean state of biases in the tropical Indo-Pacific Ocean. However, current coupled models have biases in their mean monsoon simulations. Kim et al. compared seasonal skill from two state-of-the-art latest global coupled models from European Centre for Medium Range Weather Forecasting (ECMWF) and National Centre for Environmental Pre-
diction (NCEP), USA. It is noted that the current models are superior compared to their earlier versions, where they capture well the large-scale monsoon wind variability and have better skill than persistence for rainfall for Asian monsoon. The models have best skill over the tropics compared to higher latitudes, which is related to better simulation of ENSO and its amplitude in the earth system. Monsoon–ENSO variability is also captured well in the newer models. However, for monsoon, these coupled models have biases seen in SST, low-level wind and rainfall, and also it is seen that the precipitation skill is still poor. It is believed that the source of predictability in extended range (month to a season) for the South Asia region comes from the intraseasonal variability (ISO). As the ISO plays a dominant role, if they are not simulated realistically, the seasonal average rainfall coming from the simulated ISO will naturally have biases.

Understanding the monsoon variability from days to a season is vital for model development and realistic simulation of the present-day scenario and future changes of climate state. The international scientific community under the coupled model inter-comparison project CMIP5 is studying the simulation skill of monsoon rainfall variability. Simulation of intraseasonal variability remains problematic. Due to prevailing model biases for the Indian Ocean region and discrepancies among model simulations, the projected changes in monsoon precipitation climate still remain uncertain. Realistic simulation of monsoon ISO, the monsoon–ENSO variability in these coupled models could be the key to simulated future changes in monsoon rainfall under climate change scenario. These ISO simulations and removal of model biases are closely related to the model errors originating during the first few days to weeks. Therefore, it is more relevant to study the model biases in a seamless framework, and realistic simulation of monsoon ISO is the key and remains the most challenging task for the modelling community.

In this study, we report recent results from the monsoon simulations at both medium-range and seasonal timescales and discuss the nature of its biases. These results are from the unified seamless modelling system that has been recently implemented at NCMRWF. The medium-range forecast biases are from a high-resolution atmosphere-only model, whereas the coupled model simulations are from a relatively coarser resolution. Using this advanced assimilation-modelling system, the future plans are also discussed.

**Modelling system**

The monsoon system involves multi-scale interaction among atmosphere, land surface, ocean, cryosphere and biosphere. Ideally, the model should be able to represent these processes and the model resolution should be good enough to allow realistic interaction among the said components. At NCMRWF the unified modelling system of UKMO is further being developed jointly for monsoon over different space and timescales (days to a season). Currently, for medium-range forecasts, a global high resolution (25 km at mid-latitudes) having 70 layers in the vertical with 4D variational atmospheric data assimilation has been set up. A detailed description of the implementation of the ‘NCMRWF Unified Model’ (NCUM) system can be found in (ref. 37). The grid point atmospheric model has non-hydrostatic dynamics which can handle all scales of motion. It has all the latest physical parameterization schemes taking care of surface exchanges, non-local boundary layer mixing, mass flux-type convection, interactive cloud-radiation, orography based on high-resolution elevation data and gravity wave drag. The 4D variational data assimilation system uses all global conventional and satellite data. A vast amount of satellite radiance data from different sensors is assimilated as direct radiance. This unified atmospheric model can easily be configured to a higher resolution regional nested model over the area of interest. At NCMRWF, a 12 km version of regional Unified Model (UM) has been set up nested within the global model. A further very high resolution model of 4 km was also tested for Delhi region nested within the Indian domain 12 km regional UM (Figure 1). These very high resolution models are suitable for realistic representation of local-scale heavy rainfall.

It has the potential to be configured as a convection-permitting model at 1.5 km model resolution for monsoon.

**Figure 1.** Domain of configurations of NCMRWF Unified Model.
The unified modelling framework software can easily incorporate other modules like ocean, sea-ice, land-surface, etc. into the full modelling system desired. The current NCMRWF coupled system configuration consists of a global coupled ocean–atmosphere general circulation model to calculate the evolution of ocean and atmosphere simultaneously. The NCMRWF coupled modelling system is being jointly developed for monsoon prediction with UKMO. The core model is the latest coupled UKMO HadGEM3AO system. It comprises of a range of specific model configurations incorporating different levels of complexity, but with a common physical framework. The HadGEM3AO family includes a coupled configuration, with or without a vertical extension in the atmosphere to include a well-resolved stratosphere, and an earth-system configuration which includes dynamic vegetation, ocean biology and atmospheric chemistry. The atmosphere, ocean and sea-ice are coupled using a version of the OASIS coupler developed at CERFACS in France. This coupler is used to interpolate between oceanic and atmospheric grids with a coupling interval of 3 h, which allows some resolution of diurnal cycle. A Gaussian method is used for interpolation in both directions, which automatically accounts for the coastline of the two models. In the NCMRWF coupled configuration, the atmosphere horizontal resolution is roughly $1.875^\circ \times 1.25^\circ$ (roughly 140 km at mid-latitudes) and 85 layers in the vertical (50 levels are below 18 km). In the NCMRWF coupled configuration, the ocean model used is Nucleus for European Modelling of the Ocean (NEMO) in the ORCA tripolar grid configuration, which has $1^\circ \times 1^\circ$ horizontal resolution in mid-latitudes and enhanced meridional resolution near the equator ($0.33^\circ$ at the equator). In the vertical it has 75 layers resolving the upper ocean in a very fine way (1 m resolution near the ocean surface). NEMO is a community ocean modelling framework owned and maintained by a consortium of institutions. NEMO has a large user community and is used for research and operational applications. For sea-ice simulation in the coupled system, CICE, the Los Alamos National Laboratory (LLNL, USA) sea-ice model is used. A realistic sea-ice model and its proper initialization will help in capturing the recently noted variability of Arctic sea-ice as seen in 2012 summer. In the set-up for simulating up to a season, all climate forcings (aerosols, methane, CO$_2$ concentration, etc.) are set to observed values for the period 1960–2000 and follow the emissions scenario A1B afterwards. Ozone is fixed to observed climatological values and includes a seasonal cycle. In the coupled configuration the atmospheric model component has 85 levels in the vertical, with the model top height is around 85 km called as hi-top system. This hi-top model feature is useful to capture the sudden stratospheric warming (SSW) and quasi-biennial (QBO) features and their teleconnections with other major climate signals.

### Model skill for monsoon

First we see the mean monsoon simulation and biases during the 2012 season in the medium-range NWP set-up. Figure 2 shows the 850 hPa wind for Indian monsoon region, and its bias compared to the analysis. The analysis is from the 4D variational data assimilation system of the NCUM implemented at NCMRWF. The features of the low-level monsoon circulation like cross-equatorial flow, low-level westerly Somali jet and monsoon trough are brought out well by the analysis-forecast system. However, around the equator and eastern equatorial Indian...
Ocean, the model has a tendency to strengthen the easterly flow feeding into the cross-equatorial winds in the western equatorial Indian Ocean. Part of this easterly bias causes to weaken the monsoon flow in the western equatorial Indian Ocean (north of the equator). Another westerly bias is seen in the northern Arabian Sea, which ultimately strengthens the monsoon over northwest India and might supply more moisture to the monsoon trough region and the Himalayan foothills. The monsoon trough flow is also seen to be stronger compared to the analysis. This will have an impact on the systematic errors in monsoon trough region rainfall. Another noticeable wind bias is over the Bay of Bengal region, trying to weaken the monsoon flow, which will affect the rainfall bias in the northern part of the Bay of Bengal. Figure 3 shows the NCUM model rainfall simulations at day-1, day-3 and day-5, taken from real-time runs at NCMRWF. These model rainfalls are compared with the satellite and gauge-merged daily gridded rainfall data jointly prepared by IMD and NCMRWF. Compared to the observed rainfall features, the model simulations up to day-5 look quite good. The heavy rain zone of the west coast and eastern part of the Bay of Bengal are comparing well. The monsoon trough and the rain-shadow zone in southeast part of India are also simulated well. However, by day-5 we start noticing some biases. One excessive rainfall band near the equatorial India Ocean (70°E, 5°S) is quite noticeable. Figure 4 shows the bias (forecast minus observation) of NCUM rainfall from day-1 through day-5. The said equatorial Indian Ocean positive bias is the most dominant one. This positive rain bias is also seen in the southern part of the Bay of Bengal. Most of the peninsular Indian land region (south of the monsoon trough) has a dry bias. The monsoon trough and the region north of the monsoon trough (Himalayan foothills) have wet bias. These are the model biases in very early days of the model forecast (up to day-5), which represent the case of monsoon 2012. Though the model biases are similar for other recent years, we have to analyse more years in the context of initialized NWP runs.

Mean monsoon from model simulations, also known as model climate, shows the capability of the model to capture the complex processes of monsoon. In the model the simulated variability is also related to the mean monsoon.
In a recent study of seven coupled model hindcast data, it was seen that the models that more closely replicate the observed climatological mean tend to have better skill in seasonal forecasting. In a recent study, the importance of model climate for issuing a real-time forecast to users has been shown. The skill of capturing seasonal monsoon in two state-of-the-art coupled models from ECMWF and NCEP is discussed in the detailed diagnostic work by Kim et al. Next, we examine the model output from coupled NCUM runs. Here the start date is 9 May, and we did hindcast runs in NCMRWF HPC system from 1996 to 2009. The coupled NCUM was integrated for six months stretching up to 31 October for each of the above-mentioned years. The JJA mean features were computed from these hindcast runs, and were compared with European Reanalysis (ERA) reanalyses data. ERA and Xie–Arkin monthly rainfall were used as observed gridded data for model comparison. The seasonal monsoon features of the atmosphere and oceans as simulated in the coupled model are discussed now. The first-order ocean diagnostics like the sea surface temperature (SST) and sea surface salinity (SSS) are examined. Figures 5 and 6 show the global coupled model simulated SST and SSS for a monsoon representative month of July for the whole hindcast period, and their comparison with mean observed features respectively. Reynolds SST and WOCE data for SSS are used here as observations. In a broader sense, the SST simulation for July looks good, with small biases. The SSS simulations also look good compared to observations. However, in the Indian Ocean the gradients of the SSS are sharper compared to the observations.

Now we examine the mean monsoon atmospheric conditions simulated by coupled NCUM from the said hindcast dataset. Figure 7 shows the coupled model simulated mean sea-level pressure (MSLP) for monsoon period along with observations from ERA. While plotting, to avoid values near high mountain regions, a data mask is used to remove values at heights higher than 925 hPa of pressure level. The monsoon trough region (lower values of MSLP) over central India extending to the northern Bay of Bengal region is simulated well in the coupled model. However, over the north Indian region the model produces a stronger monsoon trough, as seen in the bias plot. From this we note that the model simulates a stronger monsoon compared to ERA observations. This will have an impact on model rainfall bias. A wet bias over northwest India, including the Pakistan region is expected, which was seen in the NWP medium-range model rainfall simulation bias in Figure 4. Similar wet bias in rainfall is also expected from the coupled model, which exhibits deep monsoon trough.

Figure 8 shows the coupled model-simulated near-surface temperature (T2m) and its comparison with ERA observations, and the model bias. The mean surface temperature is simulated quite well capturing the warmer northwest India region (desert area), matching well with observations. Another warm, dry region near Chennai (east coast of India) is also captured well. The temperature biases are very less. Figures 9 and 10 show the coupled model-simulated low-level (850 hPa) and upper-level (200 hPa) winds along with ERA observations and the respective biases. The low-level wind flow is the heart of the monsoon system, strongly linked to the moisture convergence and rainfall distribution. The cross-equatorial flow, low-level westerly Somali jet and monsoon...
trough are captured well in the coupled model, as seen in the 850 hPa flow pattern. At 200 hPa level (Figure 10), the mid-latitude westerly system, the Tibetan anticyclone and the tropical easterly jet are matching well with ERA observation patterns. The core of the tropical easterly jet is seen to extend across the African continent. However, the low-level flow in the coupled model is stronger compared to observations. The bias plot brings out clearly the intensification of low-level flow over the Arabian Sea and convergence around the west coast of India. This Arabian Sea flow intensification gets a feed also from the easterly winds in the east equatorial Indian

Figure 5. Mean July sea surface temperature (°C) from 14 seasons’ hindcast of coupled NCMRWF Unified Model and comparison with observations.

Figure 6. Mean July sea surface salinity (psu units) from 14 seasons’ hindcast of coupled NCMRWF Unified Model and comparison with observations.
Ocean region. Over the Bay of Bengal there is a north-westerly wind bias, weakening the monsoon there. These low-level wind biases are similar to the model errors discussed in the NWP context in the medium range. The stronger westerly over the Bay of Bengal region forms a cyclonic wind bias around the eastern part of the Bay (Arrakan coast), which will result in excess moisture convergence and associated rainfall. The coupled model-simulated mean monsoon rainfall, corresponding to observations from CMAP rain47 and the model bias are shown in Figure 11. The distribution of monsoon rainfall from the coupled model looks quite realistic. The observed rainfall maxima over the west coast, monsoon trough, northeastern Bay of Bengal and the rainshadow region of southeast India are brought out well. The rainfall distribution shows that the coupled model has a good representation of monsoon, which is consistent with model-simulated MSLP and low-level flow patterns. The biases in the mean monsoon coupled model simulations are consistent with biases in low-level flow and MSLP distribution. The equatorial rainfall bias might be related to the equatorial low-level wind bias. The wet bias over
the west coast and monsoon trough region is related to the stronger monsoon flow in the model. Another wet-bias region is the northeast part of the Bay of Bengal (Myanmar coast region), which is again related to the cyclonic low-level wind bias there. Over peninsular India (south of the monsoon trough), there is a slight dry bias region. Interestingly, these rainfall mean biases in the coupled model are mostly similar to the day-5 forecast rainfall bias in the medium range coming from high-resolution global NWP set-up for monsoon 2012. Of course, we have to examine the mean rainfall bias in the NWP context by taking model output from more monsoon seasons. From this analysis of model output, it is not possible to say more about the location and intensity of the mean monsoon rain biases. In a recent study it is shown that in the coupled system, the cold bias over the Arabian Sea region could be a possible reason for less monsoon rainfall over India region\(^48\). A more in-depth study and much more experimentation with this coupled model will be required to understand the source of error and its growth from days to season.

**Way ahead**

To further refine the coupled models, improving the MJO/MISO simulations will be the main focus of research in the coming years at least for monsoon and the Indian Ocean region. During 2013, it is planned to increase the horizontal resolution of atmospheric component to around 85 km and the ocean component to 25 km. Moving towards higher model resolution, particularly for monsoon/tropics is important, as it will help resolve sub-synoptic and mesoscale features\(^49\). For capturing the South Asia land precipitation during monsoon, very high-resolution coupled model is required with high-capacity computing machines\(^50,51\). With coupled model, realistic representation of MJO variations especially over the Indian Ocean region also need further research\(^52\). Depicting its propagation and traversing the Maritime Continent into the western Pacific is a challenging task. Improved initial conditions of ocean–atmosphere system are of great importance in this context. At NCMRWF, the ocean initialization scheme, NEMOVar, compatible to the ocean model is being implemented. This scheme will use all available in situ temperature and salinity data, surface forcing from UM short-range atmospheric forecasts, SST analyses, sea-ice concentration/extent estimates and satellite altimetry measurements to create the best estimate of ocean state. NEMOVar is an advanced ocean data assimilation system, which was made operational recently at ECMWF for its coupled forecast system. This will make use of the upcoming altimeter data from SARAL/AltiKa. MoES is also enhancing Indian Ocean observations gradually to better define the initial ocean state in coupled models.

The global NCUM will be upgraded to 15 km horizontal resolution. The nested regional UM for India domain will also be upgraded to 8 km. NCMRWF has completed experiments with surface wind data from Indian satellite Oceansat-II, and the same is being put into operational
UM runs now. Experiments are on to include Megha-Tropiques data into the system. The upcoming INSAT-3D satellite radiance data will also be assimilated to the UM 4D variational system. With mesoscale observing network from India Meteorological Department (IMD), a regional UM-based 4D variational data assimilation scheme may be made operational at NCMRWF. To verify the model simulations there is a requirement of high-resolution gridded daily and even hourly rainfall datasets. High-resolution realistic observed gridded daily dataset from reanalysis products is required for model validation and development. Daily rainfall dataset will be useful to study the space and timescales of the northward-propagating convective rainfall bands during summer. Uncertainty of representing tropical intraseasonal rainfall variability among various reanalysis datasets is a cause of worry. It is desirable that a high-resolution 4D variational data assimilation system be used where observed rainfall, moisture, and wind information could be assimilated specially for the monsoon region to create a reanalysis dataset. NCMRWF has initiated this joint work.

In the tropics/monsoon, there are some uncertainties in forecasts because the observations with which the models are initialized are incomplete, and the models are also not perfect. These uncertainties will be taken into account by making an ensemble of forecasts, intended to cover the range of possible outcomes consistent with imperfections in the initialization and modelling systems. In addition to estimating uncertainties, these ensembles can also be used to provide probabilistic information that can be extremely valuable in many areas of weather/climate applications. One way to cater to the model uncertainties will be by representing them through the use of stochastic physics schemes, effective as seen from current research. Both for the medium-range NWP and coupled system ensemble runs of several members will be set-up next year with the availability of more computing resources.

Land-surface processes provide significant feedback to monsoon rainfall variability, and hence a realistic detailed land-surface model along with its proper initialization is an import factor in simulation/prediction of monsoon rainfall in different timescales, including implication on monsoon climate change studies. In future, JULES advanced land-surface model and the corresponding land-surface data assimilation scheme will be used in the NCMRWF coupled modelling system for the seamless prediction system development. This will enable dynamic evolution of land-surface and vegetation parameters interacting and modulating the monsoon flow. There is still much more research work to be done in this developing area of tropical/monsoon meteorology. After the onset of monsoon near the southern tip of India, northward propagation of rainfall band in June is sensitive to soil moisture and associated feedback processes, for which a realistic land-surface scheme (and corresponding initialization) has to be integrated to the modelling system. Due to human activities the land use, greenhouse gas emission and aerosols have to be considered seriously in the modelling systems. Seeing the complexities of the earth system modelling, where one has to introduce the impact of living organisms, human responses and chemical reactions, it is possible that a new generation of models will be needed to handle the multiscale nature of the climate system.


