Monsoon Mission

Science and Implementation Plan

Dynamical Prediction System

Improving Prediction Skill

Human Resource Development

International Collaboration

High Performance Computing

सत्यमेव जयते

Earth System Science Organisation (ESSO)
Ministry of Earth Sciences
Govt. of India

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Government of India

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Science and Implementation Plan for The Monsoon Mission

Contributors: IITM, NCMRWF, IMD, INCOIS, IISC, MoES

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Foreword

(Secretary, MoES)

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Chapter 1: Summary

In recent decades dynamical numerical models have considerably improved in short- medium range and seasonal prediction. Most of the state-of-the-art global coupled models have good prediction skill of El Nino /Southern Oscillation (ENSO) Sea Surface Temperature (SST) with six months lead time. The hindcast skill of seasonal mean rainfall, one season in advance, over the central Pacific is also very good. However, not much breakthrough has taken place in improving the prediction skill of Indian summer monsoon rainfall. In India, historically statistical models have been used for operational long range forecasts. However, over the years, no appreciable improvement in prediction skill was noted in spite of better understanding of monsoon variability and teleconnections. Moreover, statistical models have constraints in predicting monsoon rainfall in high spatial and temporal resolutions. In recent times, with the dynamical models, several new approaches (high resolution, super parameterizations, data assimilation etc.) have shown that the variability in tropics can be reasonably resolved, thereby creating optimism for improving the monsoon prediction. Although many centers in the world use dynamical model framework to predict seasonal mean climate routinely, in India such a frame work has to be put in place. Keeping in view the above, Ministry of Earth sciences has launched the “Monsoon Mission” to develop a dynamical prediction framework and to improve the skill of monsoon prediction. While the concerted efforts, by various research and academic institutes in India and abroad, are commendable towards developing/ improving the current generation of dynamical models to improve the monsoon rainfall prediction, with improved insight of the entire complex phenomena, greater success can be achieved for prediction of monsoon rainfall on different time scales. Under this mission the computational facilities at various ESSO-MOES institutes will be made available to academic institutes that will be participating in the national mission.

Recognizing the fact that such a complex problem needs national effort involving academic and R&D institutes, Ministry of Earth Sciences through the "National Mission of Monsoon" will involve all relevant organizations and research institutes for improving the dynamical prediction of monsoon weather and climate.

The Monsoon Mission will be undertaken through two sub-missions pertaining to two different time scales viz.,

(i) Seasonal and Extended range scale

(ii) Short and Medium range scale (up to 10 or 15 days)

It is important to bear in mind that whereas in research projects, the criteria for success is generally the demonstration of the potential for improvement in skill (with suggested changes in the model or more data on the clouds, ocean etc.), the deliverable of a mission will have to be an unequivocal demonstration of improvement in skill. The approach adopted to take this into account is as follows:

(i) setting up a framework for generating dynamical forecasts from short range to seasonal time scales, and
(ii) improvement of the skill of all forecasts from short range to seasonal.

Achieving these goals involve,

(i) implementing suitable models and data assimilation systems.

(ii) The more difficult task, by far, is the requirement to carry out R & D to improve the skill of the forecast of the Indian summer monsoon rainfall at both time scales. This may be achieved through improved parameterization, ingesting more observations (especially satellite observations), improved assimilation techniques, enhanced resolution and improved techniques for land-ocean-atmosphere coupling etc.

(iii) It is equally important to have continuous objective assessment of any changes towards the improvement of the skill that needs to be pre-defined.

1.1 Sub-Mission on "Seasonal and Extended Range prediction"

The aim of the sub-mission is to achieve discernible improvement in the simulation/ retrospective prediction of the inter-annual variation of the all-India summer monsoon rainfall (and the summer monsoon rainfall over a few homogeneous zones, if possible) with dynamical models over a time span of 5 years.

IITM will coordinate the sub-mission on improving seasonal and extended range prediction of monsoon rainfall. Preliminary background studies by IITM indicate that the Climate Forecast System (CFS) model of NCEP captures the seasonal mean and possesses some reasonable prediction skill of seasonal mean and intra-seasonal oscillations reasonably well. Therefore this model provides a reasonable base system for future development/improvements.

To improve the simulation and prediction of monsoon rainfall of seasonal mean and active-break cycles, it is proposed to carry out extensive R&D work on the following:

(a) On improvement of the physical processes in the model: coupled (one tier system), atmospheric and oceanic (two tier system)

(b) On improving the Initial conditions

(c) Forecast of SST for atmospheric models

1.2 Sub-Mission on "Short & Medium range scale (up to 15 days)"

The aim of the sub-mission is to achieve discernible improvement in the prediction of the monsoon in the medium range scale (up to 15 days in advance) with dynamical models over a time span of 5 years.

NCMRWF will coordinate the sub-mission for weather prediction up to 15 days temporal scale. Currently, operational short and medium range forecasting is done by IMD using the GFS (T574L64) model with 3-D var data assimilation. This system was first installed, tested and evaluated by NCMRWF and later made operational at IMD. It was deliberated and decided that for extending the capability beyond seven days, it is pertinent that one should utilize a coupled ocean atmosphere model. The ongoing collaboration between NCMRWF and UKMO will enable use of unified model (which uses 4D VAR assimilation system) based coupled model that has shown promise to be utilized through the entire medium range scale.

For improving the skill of such model, it is essential to optimize all kind of observations (especially from satellite), land surface assimilation and parameterization of various physical processes. NCMRWF will test, implement, validate and work on improvement of the unified model (UM) while IITM will do the same for the NCEP CFS-GFS system.

1.3 A Strategy for model improvement

Over the past 4-5 decades, a considerable amount of basic research in the country has led to better understanding of the Asian monsoon system and its variability. Unfortunately, there is a serious disconnect between the academic community and the operational weather and climate prediction agencies. As a result, the advances made in the Monsoon Science have not been translated to improvement of skill of operational forecasting models. One goal of the Mission is to leverage this knowledge base in trying to improve skill of weather and climate forecasts by forging a working partnership between the academic community and operational agencies.

It is recognized that the improvement of skill of forecast models through implementation of improved physical parameterization and data assimilation is a slow process and requires engagement of a large team of dedicated trained scientists. While NCMRWF and IITM will work vigorously on improvement of the two modeling frameworks, the skilled manpower in both the places is highly sub-critical. Since the implementation resources in MoES organizations will not be sufficient to achieve the above project goal within the proposed time frame, it is proposed that research proposals will be invited on forecast objectives from national and international Institutes/ Organizations/ Universities, so as to bring together the expertise of different Scientists / Organizations to work on the proposed Modeling framework.

All such research proposals will be encouraged from Indian as well as International scientists who will submit the proposals to work towards the above goal. While engaging the best in the world in improving the skill of the Indian operational models, a 'capacity building' concept is also built in. With each of the major proposals (especially international projects), one or two young scientists from Indian organizations (preferably from MoES organizations) will be fully associated and will be part of the R & D. These scientists will get trained by the PI & his/her team at the PI organization in particular aspect of the model development (which will benefit the MoES organizations towards specific model development works) and eventually implement the development in the Indian operational model, in association with the PI and his/her team. In this manner, it is hoped to create a substantial pool of young scientists in India capable of doing cutting edge model developments. MoES organizations will fund the cost of foreign deputation of such scientists (through Monsoon Mission funds) for their visit to PI organization of International projects of Monsoon Mission and the PI will arrange for the office space, computing resources for the associated scientist. Thus, capacity building as well as model development will be incorporated simultaneously.

It is expected that after end of 5 years, suitable Indian model(s) with improvements in simulation and forecast of monsoon weather and climate on all time scales is expected to be developed. It is proposed that after successful implementation in skill of Seasonal and Extended Range and Short and Medium range scale (up to 10 or 15 days) prediction, the modeling framework will be transferred to IMD for its operational use.

Chapter 2: BACKGROUND

2.1 Seasonal Prediction

Indian Summer Monsoon Rainfall amounts to more than 80% of the annual rainfall over India and the dependence of agriculture, drinking water and energy production on it makes it the lifeline for a large fraction of the world’s population. The economy, life and property in the region are vulnerable to significant variability of the ISM on intra-seasonal, inter-annual and inter-decadal time scales (Webster et al. 1998, Krishnamurthy and Goswami, 2000, Goswami et al. 2006a). Although the year-to-year variation of seasonal mean all India rainfall (ISMR) is only about 10% of the mean (86 cm), there is strong link between the country's food production and even the gross domestic product (GDP) on it (Gadgil and Gadgil, 2006). Hence, predicting the seasonal mean ISM rainfall is of great socio-economic importance and has been attempted for many decades, albeit with limited success (Gadgil et al. 2005, Kang and Shukla, 2006).

Forecasting Indian monsoon rainfall has a long history and dates back to 1886. The first official seasonal monsoon forecast was issued by Sir Henry Blanford in 1886 which was based entirely on Himalayan snowfall. John Eliot used extra- Indian factors, viz., and pressure of Mauritus, Zanzibar and Seychelles in the monsoon forecast of 1896. Sir Gilbert Walker who laid the basis for a forecast on a statistical association, was the first meteorologist who systematically examined the relationship between Indian monsoon rainfall and global circulation parameters and selected 28 predictors to issue forecast based on regression equation during the year 1906 (Jagannathan 1960; Rao and Rama Murthy 1960; Rao 1965). Savur (1931) showed that 7 out of 28 parameters have lost their significance in course of time. Since then, extensive research work has been done on empirical seasonal forecasting of Indian summer monsoon rainfall. In spite of several changes in operational empirical models of IMD, based on extensive research work since 1932, no significant improvement in prediction skill of Indian Summer Monsoon Rainfall has realized (Gadgil et al., 2005; Fig.1). At present, IMD uses a statistical prediction system (Rajeevan et al. 2007) for operational long range forecast of the Indian monsoon rainfall.

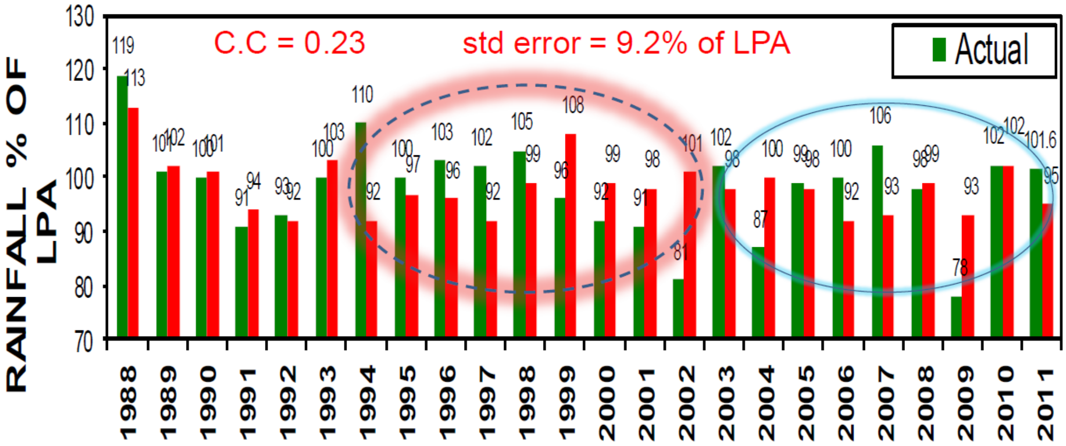


Fig. 1: Performance of operational forecast (empirical model) for all India rainfall.
(Source: Dr. D. S. Pai, IMD, Pune)

Dynamical predictions of the Indian summer monsoon rainfall with models of the stand alone atmosphere and/or coupled ocean–atmosphere models based on physics have become reality in the last couple of decades because of the rapid developments in weather and climate science and high performance computers. In spite of rapid advances in atmospheric sciences, simulation and prediction of the Indian monsoon remains a tough challenge (Wang et al., 2005, Gadgil and Srinivasan, 2011). Wang et al., (2005) have shown that the state-of-the-art atmospheric general circulation models (AGCMs), when forced by observed sea surface temperature (SST), are unable to simulate properly Asian-Pacific summer monsoon rainfall (Fig.2).

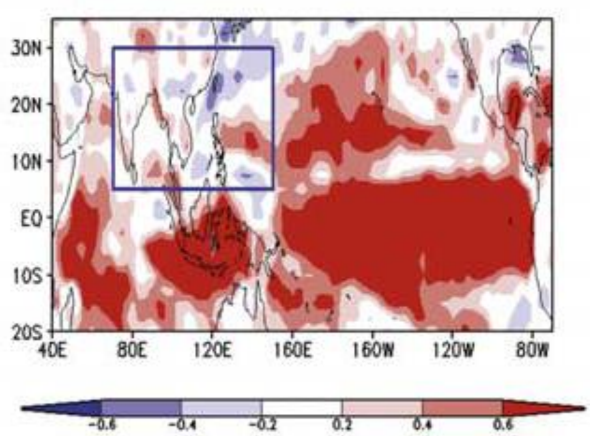


Fig. 2: Correlation coefficients between the observed CMAP (1979–1999) and the simulated June–August precipitation anomalies made by five-model multi-ensemble mean (adopted from Wang et al., 2005).

There is considerable observational and modeling evidence that the Indian summer monsoon (ISM) is governed largely by coupled ocean-atmosphere processes. For example, ENSO is a major driver for ISM and as ENSO is clearly a coupled phenomenon, a coupled ocean-atmosphere GCM is crucial for monsoon prediction. In yet another study, Kumar et al. (2005) have shown that the "perfect model skill" could reach up to 0.65 if the SST could be forecasted accurately. But, the actual simulation skill of an AGCM is much lower than this, however, they have discovered that the skill improves significantly once the AGCM is coupled to a mixed layer model suggesting that monsoon prediction involves the coupled ocean-atmosphere processes (Fig. 3).

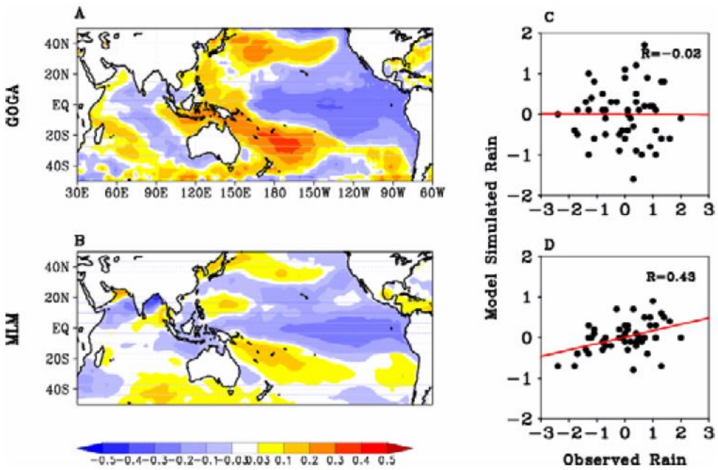


Fig. 3: Correlation maps of (a) observed SSTs and monsoon rainfall simulated from uncoupled GFDLR30 (GOGA) model, (b) simulated SSTs and monsoon rainfall from the coupled (MLM) model. Scatter plots of standardized anomalies of observed and simulated monsoon rainfall for each year during 1950–1999 from GOGA and MLM are shown in (c) and (d), respectively. (adopted from Kumar et al., 2005)

An attempt to assess the skill, of standalone atmospheric models used in India, in simulating the inter-annual variations of the ISMR by prescribing observed SST was taken up in 2004/2005 under the Seasonal Prediction of Indian Monsoon (SPIM) project sponsored by the Department of Science and Technology (DST). This exercise was meant to provide the measure of potential skill that can be achieved by these models, which is not exactly the prediction skill. The results of this project showed that only one model is having moderate skill of 0.39 in simulating the inter-annual variability of ISMR and other models do not show any significant skill. The prediction skill of these models is not known. All these findings laid path for looking at coupled ocean-atmosphere models for possible improved seasonal prediction of monsoon rainfall.

Recent studies have examined the skill of coupled models in predicting the ISMR and noticed that the skill is better than the empirical models and standalone AGCMs. Preethi et al. (2010), using a set of 7 fully coupled models from European centers (DEMETER), have shown that the multi model ensemble skill of these 7 coupled models is about 0.28, however, the individual model skill varies between -0.3 to 0.43. In a subsequent study, Rajeevan et al. (2012) have shown that the skill of individual models and multi-model ensemble (MME) is further improved in the state-of-the-art European models (ENSEMBLES) with improved physics and dynamics. The skill of the individual models varied between 0.27 and 0.45. The studies of Delsole and Shukla (2012) and Nanjundiah (2013) also suggested that the recent coupled models have improved their skill in predicting the ISM. These studies highlight that the skill of seasonal forecast of ISMR by coupled models have steadily improved during the past decade to a threshold such that any further improvement in skill will make these dynamical forecasts very useful to the users. Thus, this is an opportune time to engage the coupled models for monsoon prediction.

2.2 Extended Range Prediction of Active/Break Cycles of Monsoon

As is known from earlier studies, the monsoon rainfall is not continuous and is punctuated by active and break cycles (Goswami, 2005). Satellite observations have revealed that the active and break of south Asian monsoon or the wet and dry spells over the Indian continent, are manifestation of repeated northward propagation of the tropical convergence zone from the equatorial position to the continental position [Sikka and Gadgil, 1980; Yasunari, 1979] and results from superposition of a 10-20 day and a 30-60 day oscillations. Both the 10-20 day oscillation and the 30-60 day oscillation contribute roughly equally to the total intra-seasonal variability (ISV) in the south Asian monsoon region. While 30-60 day oscillation has a very large zonal scale encompassing both the south Asia and the East Asia/West north Pacific monsoon regions, the 10-20 day oscillation has a smaller zonal scale and is regional in character. The 30-60 day mode is characterized by a northward propagation while the 10-20 day mode is characterized by a westward propagation. It indicates that relative frequency of occurrence of active and break phases could influence the seasonal mean and contribute to the inter-annual variability (IAV) of the SAM. The amplitude of intra-seasonal variability (ISV) of ISM is very large and represents a large signal and hence is likely to have large potential predictability. While the amplitude of inter-annual variability (IAV) of ISM rainfall over relatively smaller spatial scale is about 20% of the mean, the amplitude of ISV of rainfall is as large as the mean (Goswami et al. 2011, book chapter, ed. C. P. Chang). Several studies (Goswami and Xavier, 2003, Waliser et al. 2003) have made estimate of potential predictability of monsoon ISO's to be about 25 days (Fig.4). This knowledge prompted many studies to attempt to develop techniques for predicting Indian summer monsoon ISV.

The skillful and timely forecasts of intra-seasonal monsoon rainfall possess a greater potential utility for agriculture and water resource management (Goswami, 2005). There have been several important research studies in the recent past using both statistical and dynamical methods for the extended-range prediction of the Indian summer monsoon intra-seasonal oscillation (ISO) and its active and break spells. Lo and Hendon [2000], Mo [2001] and Jones et al. [2004] used statistical techniques for the skillful long-range prediction of the Madden-Julian Oscillations. Goswami and Xavier [2003] used an empirical model for the prediction of intra-seasonal monsoon breaks 18 days in advance. Webster and Hoyos [2004] used wavelet banding to develop a prediction scheme for the prediction of intra-seasonal rainfall and river discharge on 15–30 days timescales. Using the insight gained from nonlinear dynamical system theory Dwivedi et al. [2006] developed an empirical rule for the extended range prediction of duration of Indian summer monsoon breaks. Dwivedi and Mittal [2007] forecasted the duration of active and break spells in Intrinsic Mode Functions of ISOs. Xavier and Goswami [2007] used analogue technique for real time forecasting of ISOs. Waliser et al. [2003]

estimated the limit of dynamical predictability for the tropical ISO using an atmospheric general circulation model. They also explored the influence of strength and phase of the ISO on the predictability limit. The impact of air-sea coupling on the predictability of ISO has been investigated with an atmosphere-ocean coupled model and its atmospheric component by Fu et al. [2007]. Fu et al [2007] have noticed that ISO prediction using coupled models was improved by 5 days (Fig. 4). Fu et al. [2009] examined the sensitivity of monsoon intra-seasonal forecasting to different initial conditions using coupled model. An attempt was made to develop a statistical technique using the Artificial Intelligence (AI) for the very long-range prediction of the ISO data. The Genetic Algorithm (GA) and Artificial Neural Network (ANN) are used as AI models for this purpose. In a recent study, Chattopadhyay et al., (2008) have shown the ability of Self Organizing Maps (SOM) technique to isolate spatial structure and evolutionary history of nonlinear convectively coupled states of the summer monsoon ISO. This knowledge is used to develop an analog technique for predicting different phases of monsoon ISO. Skillful four-pentad lead prediction of rainfall over central India is demonstrated with the model using only large-scale circulation fields. A major strength of the model is that it can easily be used for real-time extended-range prediction of monsoons.

Several studies (Sengupta et al. 2001, Fu et al. 2003) have demonstrated that ocean-atmosphere interaction plays a crucial role in defining the space-time spectra of summer monsoon intra-seasonal oscillations (MISO). Using a coupled model Fu et al., (2007) have shown that the MISO predictability is generally higher over the Indian sector than that over the western Pacific with a maximum of 35 days in the eastern equatorial Indian Ocean. Air–sea coupling significantly improves the predictability in almost the entire Asian–western Pacific region. The mean predictability of the MISO-related rainfall over its active area (10°S–30°N, 60°–160°E) reaches about 24 days in the coupled model and is about 17 days in the atmosphere-only model. This result suggests that including an interactive ocean allows the MISO predictability of an atmosphere-only model to be extended by about a week.

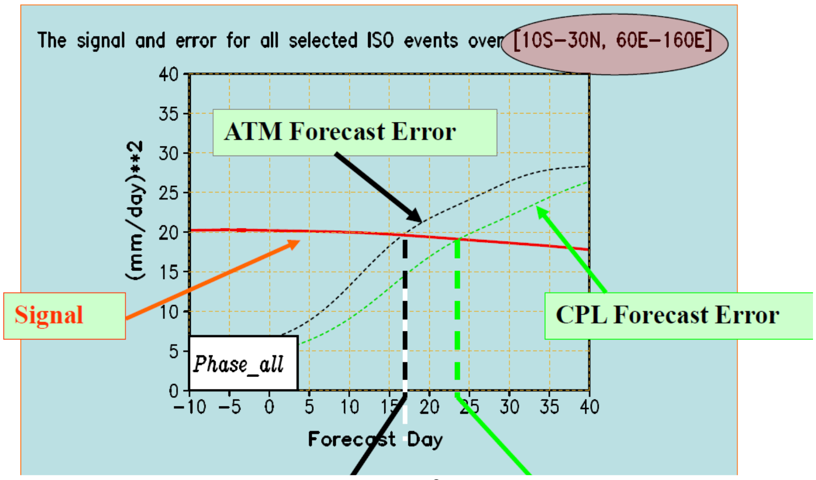


Fig. 4: The rainfall signals and forecast errors (mm/ day)^2 as function of lead time averaged in the Asian–western Pacific region (10°S–30°N, 60°–160°E) for all selected MISO events (Fu et al., 2007)

2.3 Short and Medium Range Prediction

Monsoon Forecasting is a challenging problem over the Indian subcontinent where monsoon constitute a major weather system affecting a large population. Short & medium range and seasonal forecasts are essential for various weather sensitive activities such as farming operations, flood forecasting, water resource management sports, transport etc. Forecasting monsoon weather system and associated rainfall is one of the difficult areas in Numerical Weather Prediction (NWP) due to complex interactions involved. These include impact of topography, treatment of synoptic scale systems, mesoscale convective systems and non-availability of good quality high resolution observations over land and ocean.

IMD has the operational mandate to provide day to day forecasts on short to medium range for various user specific application such as, public weather services, aviation, agriculture, hydrology, disaster management etc. In the past, synoptic methods have been the mainstay of tropical weather forecasting. Of late, NWP methods have acquired greater skills and are playing increasingly important role in the tropical weather prediction, through the progress of dynamical modelling efforts in the tropics has been rather slow as compared to the extra tropics. This is because of some inherent problems associated with the dynamics of the tropical systems. In the extra tropics, the primary energy source for the atmospheric motion is the zonal available potential energy associated with the strong temperature gradients, and there exists a satisfactory dynamical theory of these motions outside the tropics. In the tropics, on the other hand, the storage of available potential energy is very small due to the very small temperature gradients. Latent heat release in cumulus convection is the primary energy source. Parameterization of cumulus convection in tropical model is therefore very important and is a difficult problem. Added to this, there is the problem of large perennial data gaps in the tropical regions which are largely oceanic. The tropical numerical weather prediction system is required to address these problems adequately. Much progress has been made in recent years in the development of numerical models for low latitudes. The World Weather Watch, now supported by a variety of surface based and spaced based observing platforms has considerably enhanced the observational data base for numerical weather modelling. The availability of faster computers has enabled a large volume of tests on analysis, initialization, sensitivity to physical parameterization and statistical evaluation of NWP, resulting an overall improvement in the skill of tropical dynamical models.

Currently, Forecast Services are based on conventional Synoptic Methods supplemented by use of Numerical Weather Prediction products of different centres. But there is a growing demand to provide quantitative accurate forecasts in short to medium range time scale for parameters such as rainfall, temperature, humidity, wind, cloud etc. To meet this requirement NWP is the only state of the art tool currently available.

In this direction, action was initiated in the Eleventh (XI) - five year plan for a massive up-gradation of weather forecasting capabilities in India under the Modernization Programme of the Government of India, which covers various components such as, atmospheric observation network; strengthening of computing facilities, data integration and product generation and dissemination of information to an optimum level. It aimed for improved forecasting capabilities for high impact weather events like cyclones, severe thunderstorm, heavy rainfall and floods in a significant manner. IMD now has a good network of automatic weather stations, Doppler Weather Radars (DWR), state-of-the-art upper air systems etc. These observations are now being used to run numerical prediction models on High Performance Computing Systems (HPCS).

All current operational Numerical Weather Prediction (NWP) systems/models have limitations in predicting anomalous monsoon features, particularly the extreme events like heavy rainfall. A comparison of skills of global NWP systems of various leading NWP Centres of the world shows that their performance is more or less similar. When it comes to forecast during the monsoon season on short to medium range, no model has been able to predict consistently well the synoptic features beyond 4 to 5 days. No model has skill beyond day 3 in case of even moderate to heavy rainfall.

In general the NWP systems of leading global NWP centres are improving by 1 day of predictive skill per decade. However proportionate improvement in skill has not been noticed over the tropical monsoon region. The major international NWP centres have been able to invest adequate resources, both in terms of computing power and manpower for improving the skill of NWP. The improvements have been generally due to:

- ✓ Improvements in model dynamics and physics

- ✓ Better observations.
- ✓ Careful use of forecast and observations, allowing for their information content and errors - achieved by variational assimilation e.g., of satellite radiances
- ✓ Four Dimensional Data Assimilation (4D-VAR)
- ✓ Hybrid ensemble DA

A focused effort is required on the national scale for improving the assimilation and forecasting system especially for the monsoon region.

Chapter 3: Current Status of Monsoon Weather and Climate Prediction

Several academic and R&D institutes in India are carrying out research in the above fields on different models (both empirical and dynamical), including diagnostics of why the models fail to predict a particular year's monsoon performance. However, the knowledge gained at these institutes is not translated into improvement of operational weather and climate forecasts, as there is no concerted effort to link the knowledge gained at academic and R&D organizations to improve operational models as all these organizations are working at their will on different models which they can obtain easily. Therefore, there is a need of concerted efforts between the academic, R&D Institutes and operational organizations for improvement of operational weather and climate forecasts, especially using specific models which can give reasonably accurate forecast. This will require proper coordination amongst several Institutes/ organizations/Universities towards this particular goal.

3.1 Seasonal Prediction

Variations of monsoon rainfall affect agriculture, drinking water, transportation, health, power, and the very livelihood of billions of people living in the monsoon region. It is no surprise therefore that for more than one hundred years several countries have tried to issue long range forecasts of monsoons (India Meteorological Department started issuing long range forecasts of monsoon rainfall in 1886). The operational long range forecasts of monsoon rainfall were based on empirical relationships derived from past observations of atmospheric pressure, temperature and wind. Blanford (1884) was the first one to suggest the use of a surface boundary condition (snowfall over Himalayas in the preceding winter) to predict the summer monsoon rainfall over India.

From 1924 to 1987, forecasts were issued for NW India and peninsular India using separate multiple regression models. These models were updated as and when required. Verification of these forecasts (1924–1987) revealed that about 64% of these forecasts were proved correct. During the decade of 1981–90, concerted efforts made to develop new LRF techniques resulted in the development of new types of LRF models, namely dynamical stochastic transfer, parametric and power regression models. Since 1988, the long-range forecasts are issued for the country as a whole based on the 16-parameter parametric and power regression models. The parametric model is purely qualitative and it indicates whether monsoon would be wet (normal or excess) or deficient. In this model, equal weight is given to each of the 16 parameters. The power regression model is a quantitative model, which acknowledges the nonlinear interactions of different important climatic forcing with the Indian monsoon. In 2003, IMD changed the 16 parameter model and another model with 10 predictors were used. However, the same power regression technique was used. In 2007, IMD introduced the new ensemble statistical prediction system (Rajeevan et al. 2007) for the operational forecasts. The same system is being used for operational forecasts by IMD.

The verification of IMD's operational forecasts from 1988 to 2011 is shown in Figure 1. It can be seen that since 1989, ISMR has been normal (± 10%) as correctly predicted by IMD. In 1997, when there were apprehensions regarding the prospects of ISMR due to El Nino, the IMD's prediction was ultimately proved correct. However, forecast errors in some years (1994, 1997 and 1999) were more than the model error (of ± 4%). The root mean square error of the forecasts for the period 1988 to 2011 was about 7.6 %. The correlation coefficient between the actual and predicted rainfall during the period 1988-2011 is 0.23, which is just positive, but not a large magnitude. When compared to the climatology, IMD's operational forecasts were not more skill-full.

One major problem with most of the empirical models is that they are not validated on large enough truly independent samples. As a result, the skill is not a true skill but an apparent skill. Also, if many predictors are used, there is danger of over fitting. Keeping these problems in mind, IMD's operational model now has only five parameters. Errors associated with these models indicate that the models tend to predict largely the 'mean' and fail to predict the extremes.

Charney and Shukla (1977, 1981) presented a conceptual hypothesis for monsoon predictability based on the influence of the boundary forcing at the Earth's surface. A brief historical perspective on this hypothesis is given here. Charney et al. (1977) had conducted AGCM experiments with NASA/GISS AGCM to investigate the influence of changes in albedo on rainfall over Sahel. In these experiments it was found that the summer rainfall variance among the three ensemble members (each member was integrated only for 45 days) was quite small over the Indian monsoon region, indicating that the boundary conditions mainly control the Indian monsoon rainfall. In the same year, Shukla and Misra (1977) had shown empirical evidence of a possible relationship between Arabian sea surface temperature and Indian rainfall, and Shukla (1975) had shown that in the GFDL atmospheric general circulation model (AGCM), specification of (large) positive SST anomalies over the Arabian sea produced increase in monsoon rainfall over India. Hahn and Shukla (1976) revived the Blanford's hypothesis of snow–monsoon relationship by showing, using satellite derived snow cover data, an inverse relationship between the winter season snow cover over Eurasia and the subsequent summer monsoon rainfall over India. These results, combined with the results from the GISS model in which variance of seasonal rainfall among ensemble members was quite small, lead Charney and Shukla (1977, 1981) to propose a hypothesis that predictability of monsoon depends on the influence of boundary conditions at the earth's surface.

The Charney - Shukla hypothesis has been the central paradigm for monsoon predictability research during the past 25 years. However, dynamical models have had large systematic errors in simulating the seasonal mean anomalies associated with changes of boundary conditions, and therefore the potential predictability of summer monsoon rainfall has been relatively low. Whether our inability to capture the boundary forced signals is due to inadequate models and modelling strategies or due to intrinsic limits to the predictability of seasonal mean rainfall because of large natural intra-seasonal variability of monsoon remains an open question and a topic of vigorous debate. In the following section we present a critical retrospective of the Charney-Shukla hypothesis and describe the barriers to realizing the potential predictability.

For the influence of the boundary conditions to be useful to predict monsoon rainfall, the following three conditions need to be satisfied: 1. There must be a large and persistent anomaly at the earth's surface, 2. There must be a well defined dynamical mechanism through which changes in the boundary condition will produce a corresponding change in seasonal mean monsoon rainfall, 3. The seasonal mean response (signal) must be sufficiently large and reproducible so that it can be distinguished from the intrinsic variability (noise) of the model due to internal dynamics alone. A large number of model simulations during the past decade with high resolution AGCMs using advanced parameterizations have clearly shown that the internal variability over the monsoon region is much larger than that found by Charney and Shukla. Estimates of 'internal' variability by several studies (Goswami, 1998, Goswami and Ajay Mohan, 2001, Goswami and Xavier, 2005), indicate that the 'internal' IAV of the seasonal mean over the Indian monsoon region is as large as the variability induced by slowly varying boundary forcing, making the Indian monsoon an exception in the tropics and limiting its predictability. This implies that large member ensembles are needed to distinguish the boundary forced response from internal dynamics variability. If the internal variability is at small spatial scales and at high frequency, large scale spatiotemporal averages (viz seasonal mean over whole India) could be predicted if the boundary forcing were indeed important, and if the models were able to simulate the appropriate physical effects.

The current generation of AGCMs have such large systematic errors in simulating both the mean and the variance of summer monsoon rainfall that it is not possible to conclude whether our current inability to make useful dynamical seasonal prediction is due to lack of boundary forced predictability or inadequacy of the current models and modelling strategies. Recent research work in which model experiments are carried out with coupled ocean atmosphere models suggests that the prescription of SST anomalies in AGCM experiments is an inadequate modelling strategy because SST anomalies in the Indian Ocean and the adjoining western Pacific Ocean are either forced by the atmosphere or evolve as a strongly coupled ocean-atmosphere process (Wang et al. 2004). If ocean-atmosphere coupling is indeed crucial for the Indian Ocean and western Pacific SST anomalies, predictability of monsoon must be investigated with coupled ocean-atmosphere models, which currently have large systematic errors. The problem is further compounded by the fact that atmosphere-land interactions are also quite important for simulation and prediction of monsoon rainfall. Even if SST anomalies were able to force significant changes in large scale circulation, the local land-atmosphere interaction will modulate the ocean forced remote response and determine the actual changes in rainfall over land. Therefore, realistic models of the total climate system (ocean-land-atmosphere) are required to understand the predictability, and to make useful predictions of monsoon rainfall.

3.2 Extended range Prediction of active/break cycles of Monsoon

Vigorous intra-seasonal oscillations (ISOs) in the form of active and break episodes are integral part of the Indian summer monsoon (please refer Goswami, 2005 for a review). Prediction of the active and break episodes 2–3 weeks in advance is of great importance as sowing, harvesting, and water management for agriculture within the season depends crucially on the rainfall associated with these phases of the monsoon ISOs. Initially described in terms of rainfall (Ramaswamy 1962; Ramamurthy 1969) over India, the mean spatial structure of rainfall and circulation fields associated with active and break conditions (Krishnamurti and Subrahmanyam 1982; Krishnamurti et al. 1985; Webster et al. 1998; Krishnan et al. 2000; Annamalai and Slingo 2001; Annamalai and Sperber 2005; Goswami 2005) have very large spatial scale extending far beyond the Indian continent. One important character of these intra-seasonal spells is the repeated northward propagation of the zonally oriented cloud band from south of equator to about 25°N in this region (Sikka and Gadgil 1980; Yasunari 1979). Further, the nonlinear relationship between the rainfall and the large-scale circulation indicates that the active–break spells are related to a convectively coupled oscillation consistent with theory (Goswami and Shukla 1984; Jiang et al. 2004; Wang, 2005). This underlying large-scale spatial pattern together with relatively slow evolution has led to the optimism for extended-range prediction of these phases of the monsoon ISOs (Goswami and Xavier 2003; Webster and Hoyos 2004).

Lot of research work was carried in India on monsoon intra-seasonal oscillations (MISO) and active/break cycles of monsoon starting from Sikka and Gadgil (1980) to Goswami (2012). Previous studies suggested that potential predictability of Monsoon breaks is much higher than that of monsoon active conditions. Simple empirical models developed during the last couple of years (Goswami and Xavier, 2003; Webster and Hoyos, 2004) demonstrate a potential for predicting summer monsoon ISOs up to 3 weeks in advance. A limitation of some of these empirical models was that they were not suitable for real time predictions due to endpoint problems arising from the use of some form of time filters. The development of analogue models for real time forecasting of summer monsoon ISOs with a level of skill that is useful up to 3 weeks in advance (Xavier and Goswami, 2007; Chattopadhyay et al., 2008) during the past couple of years may be considered a major advance in this direction. These developments in the real time prediction of summer ISOs as well as of the MJO are reviewed in Goswami et al. (2011).

Chattopadhyay et al. (2008) developed a nonlinear analogue technique for forecasting pentad rainfall over central India four pentads in advance. The technique works on the following premise. It is proposed that monsoon ISOs arising from fluctuations of the TCZ are nonlinear convectively coupled oscillations. Thus every phase of rainfall oscillation must be uniquely related to a unique combination of large scale three-dimensional circulation parameters. Reversing the argument, if we could identify unique (distinct) nonlinear patterns (relationship) amongst the large scale circulation parameters, they may be linked to unique nonlinear phases of the rainfall oscillation. The authors achieved this by employing a nonlinear pattern recognition technique known as “Self Organised Map” (SOM, Kohonen 1990) on six large scale indices of monsoon ISO without directly involving rainfall. Within limits, SOM can be used to identify as many distinct patterns as we wish. For example, a 3x3 SOM classification would give us nine patterns or phases while a 9x9 SOM classification would give us 81 patterns or phases. Using not only current but also some past data in defining the SOM vectors, the evolutionary history may be built in defining each SOM node or phase of the ISO.

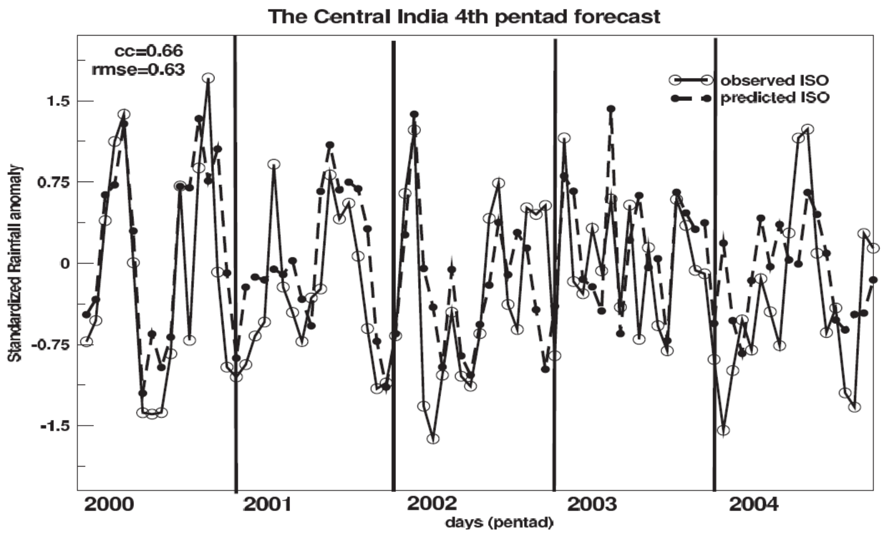


Fig. 5: Four-pentad forecast verification over central India during summer seasons from 2000 to 2004. Verification data is obtained from the IMD daily gridded precipitation (Rajeevan et al. 2006). First forecast for each year is for the pentad 20-24 June and last pentad is for 8-12 September. Forecast is made using the SOM model using six dynamical parameters and past nine days' information.

The nine phases obtained from the 3x3 SOM classification (Chattopadhyay et al., 2008) corresponds to the minimum number of phases required to represent an averaged oscillation and does not isolate event-to-event variability of the phases. To capture this feature, 225 patterns (phases) were identified using a 15x15 SOM classification. These phases included different shades of active and break conditions together with those of other phases. By minimising the distance between the SOM vector at forecast time and the 225 pre-determined patterns, a set of 'close analogues' are identified. Using the history of the close relationship between SOM nodes and rainfall, rainfall forecasts can be made from the past evolutionary history of the close analogues. The model is trained with data between 1951 and 1999 and tested by making forecasts during the independent period between 2000 and 2004. The model demonstrates good skill (Fig. 5) for forecasts with leads of up to four pentads of pentad rainfall over central India (12°N-22°N, 72°E-85°E).

In summary, a Bayesian method has been found for real time prediction of rainfall over central India with lead times of up to four pentads. Although useful skill is found over other regions of India, best skill is found over the agrarian belt of central India.

As such, no operational extended range predictions of active/break cycles of monsoon are issued by India Meteorological Department. IITM developed the above methodology to issue experimental monsoon forecasts and shared with IMD from time-to-time. Dynamical Modelling frame work was not used until 2011, to make predictions on extended range predictions of active/break cycles of monsoon.

3.3 Short and Medium Range Prediction

In India, the National Centre for Medium Range Weather Forecasting (NCMRWF), a constituent unit of the Ministry of Earth Sciences (MoES) is mandated to continuously develop next generation numerical weather forecast systems, in terms of reliability and accuracy over India and neighboring regions through research and development. This Centre was established as a mission mode project of the Government in 1988 to provide accurate, location specific medium range weather forecasts to Indian farmers using modern numerical weather prediction (NWP) techniques. The NCMRWF implemented its first global NWP system in 1992 and started giving operational forecasts in June 1994. The forecasts were generated initially using a coarse resolution (~150 km) global model

(T80/L18) and associated data assimilation system. The resolution of the NWP system was increased whenever possible within the available computing resource.

NCMRWF migrated to a new modelling framework, namely, Global Forecast System (GFS) at a resolution of T254L64 (T254 spectral waves in horizontal and 64 layers in vertical) in 2007. Subsequently the model was further upgraded to T382L64 in 2010. At present GFS at T574L64 resolution (T574 spectral waves in horizontal and 64 layers in vertical) is operational. The resolution is ~22 km in horizontal. The GFS has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geostationary satellites. Ten day forecasts are generated everyday with the initial conditions of 00UTC. The same model is also operational at IMD. High resolution meso-scale models (WRF-ARW and HWRF) are used at IMD for predicting high impact weather such as extreme rainfall, tropical cyclones etc. These meso-scale models are used for generating short range forecasts of monsoon. These models are also being used for dynamical downscaling which helps in providing location specific forecasts.

Under the MoU between MoES and UKMO, NCMRWF is implementing the UKMO's Unified Model (UM) and associated 4D-Var Data Assimilation system. Currently UM at N512L70 (~25 km horizontal resolution at mid-latitude) along with 4D-Var are being experimentally run in real-time. A regional version of the UM at 12 km resolution over the Indian monsoon region has been also setup and is being tested for select cases.

Recent studies suggest that an interactive ocean in a high resolution fully coupled general circulation model significantly enhance the prediction skill of weather in medium range. Experiments at ECMWF and other centers have started showing the benefits of ocean coupling in improving the skill in medium and 2 weeks to 1 month monsoon forecasts. The upper ocean should also have a very high vertical resolution (1 m), and the ocean model has to be called more frequently (1 hour) from the atmosphere model. Therefore ocean model with high vertical resolution in the upper ocean has to be coupled. Ocean data assimilation will be required to initialize the ocean model properly. Similarly a land surface model with its assimilation has to be also coupled to form the fully 'Coupled Earth System Model'. The whole issue of monsoon model development has to be dealt in a holistic way where the scales from hours to a season are considered together in a seamless manner. The model diagnostics and verification also has to take care of the scale interaction contributing to monsoon systems, which can be dealt when we consider hours to a season in totality.

The day-1 NWP forecast is critical in determining the day-7 forecast, and it is most likely that skill of monthly/seasonal forecasts will be determined by quality of short and medium range forecasts. World Modelling Summit held at Reading, UK in May 2008, adopted 'Seamless Prediction' as one of the important consensus theme. In annual European Geophysical Union's meet of 2009 ECMWF organised a special session on 'Seamless Prediction' approach. Artificial boundaries between mesoscale short-range prediction, synoptic scale medium range prediction, and monthly/seasonal prediction have no scientific basis. Due to practical considerations of computing and of model complexity different prediction systems for different time scales were being practices. The simulation and prediction of meso-scale systems, synoptic scale disturbances, intra-seasonal, seasonal and inter-annual variations are linked. It is suggested that future research on prediction of weather and short-term climate be carried out in a unified framework. For reliable prediction of regional seasonal climate it is essential that model accurately simulate the modes of natural variability from diurnal to seasonal scales. Utilization of the insights gained from operational weather and seasonal climate prediction, and of the synergy between the weather and seasonal climate prediction communities is essential for the development of next-generation seamless prediction systems.

Combining the above, NCMRWF submitted a proposal to MoES to develop a seamless prediction system from a state-of-art coupled modeling system mid-way during the XI-Plan and the same was approved. In view of this, UKMO-MoES MoU was expanded to incorporate coupled modelling. Under this UM based coupled model using NEMO ocean model has been setup at a coarse resolution and efforts are going on to increase the model resolution in both horizontal & vertical. Work on initializing the ocean component with NEMOVar is continuing. NEMOVar is the state-of-art ocean initialization system also being used by ECMWF and has the capacity to assimilate much more ocean data compared to any other system.

Chapter 4: Objectives

Based on the above background work, the Monsoon Mission proposes to achieve the following objectives.

- To develop a dynamical coupled ocean-atmosphere seasonal and extended range prediction system.
- To develop a dynamical modeling framework for prediction of weather on short and medium range time scales
- To achieve an appreciable and quantifiable improvement in the skill of prediction in all time scales from the present skill.
- To setup the infrastructure and development of human resources required to improve the prediction skill at all time scales
- To build a working partnership between the Academic R & D Organizations and the Operational Agency to improve the monsoon forecast skill.

To setup a dynamical coupled ocean-atmosphere seasonal and extended range prediction system at IITM/IMD.

At the time of launching of Monsoon Mission, in India, there was no coupled Ocean-atmosphere dynamical modeling frame work in place to make either operational or experimental forecasts of Seasonal mean and monsoon active/ break conditions. Under the monsoon mission, it is proposed to setup a dynamical coupled modeling framework in place so that both academic, R&D institutes work on this model to improve the model for better predictions of monsoon weather and climate.

To setup a dynamical modeling framework for prediction of weather on short and medium range time scales

Both NCMRWF and IMD presently use Global Forecast System (GFS) developed by National Centers of Environmental Prediction (NCEP) for making operational weather forecasts at short and medium range time scales. The GFS system used at these centers used to undergo updates as and when there were some improvements/upgrades were made at NCEP with slight time delay. Not much of development work took place at these centers as both these centers are responsible operational centers and the scientific manpower was completely engaged in making operational forecasts. Under monsoon mission it is proposed to setup a better modeling framework together with state of the art data assimilation system in place, so that both operational and developmental activity can take place on this framework. At NCMRWF, the UK Met office (UKMO) unified model (UM) was also implemented for short to medium range forecasts. The UM also will be improved in the prediction skill of short to medium range forecasts.

To setup the infrastructure and manpower required to improve the prediction skill at all time scales

Until recently, modeling activity in India was limited to just run the models and test its skill and make experimental forecasts on standalone AGCMS, mainly due to lack of trained manpower to work on model developments and lack of HPC infrastructure to run these models. Under the monsoon mission, it is proposed to strengthen both these aspects so that model development activity in India can take giant leap and develop its own modeling framework. HPC infrastructure will be augmented to a reasonable capacity so that all R&D and academic organizations involved in Monsoon research should get access to this and at the same time, it is very essential to train our young scientists to get exposed to new techniques in model development and analysis, so that the momentum created by the mission continues even after the end of the mission.

To build a working partnership between the Academic R & D Organizations and the Operational Agency to improve the monsoon forecast skill.

As mentioned earlier, lot of research work is being carried out at national institutes/universities on monsoon processes and forecast of monsoon weather and climate. Under Monsoon mission it is proposed to encourage national institutes/ Universities to work on the operational modeling frame work setup at MoES institutes, so that the knowledge flow from these centers can easily flow into operational centers to improve the prediction skill of the operational models and at the same time the man power working on the operational dynamical modeling framework will increase automatically.

To improve the skill of the prediction system from the existing skill

Ultimate aim of the mission is to improve the prediction skill of the dynamical models implemented at the MoES institutes to a reasonable and useful level compared to the present prediction skills. Seasonal Prediction skills will be improved by at least 20% from the present skills (acc= 0.55) and extended range predictions will be improved by at least a week from present skill (3 weeks) and short and medium range predictions will be improved by additional 2 and 5 days respectively from the present skill of 3 and 7 days.

Chapter 5: Model Selection

Since the main objective of the Mission is to setup a dynamical modeling framework, it is important to select an existing operational model from leading weather and climate prediction centers in the world. Since, in India we do not have enough trained human capital in dynamical modeling; it is not advisable to start the activity of developing a dynamical model from scratch. While selecting the model the following aspects would be considered.

1. Fidelity of the model in capturing the Indian summer monsoon features and climatology.
2. Availability of technical support in respect of model code changes
3. Skill of the model in predicting the monsoon weather and climate.

5.1 Model Selection for Seasonal and Extended Range Prediction and Work Plan (IITM)

Since, the low-frequency component of the tropical variability is primarily forced by slowly varying boundary forcing (e.g. sea surface temperature (SST), land surface temperature, soil moisture, snow cover, etc.) , which evolves on a slower time scale than that of the weather systems themselves the seasonal mean monsoon rainfall is more predictable than day-to-day weather. However, the complete monsoon system is not forced entirely by boundary forcing, but also by internal dynamics, therefore the predictability of seasonal mean monsoon rainfall is limited to some extent.

Research institutes such as IITM, CMMACS, SAC and other institutes in India have started to explore dynamical models to generate seasonal monsoon predictions. Under the project of seasonal prediction of Indian monsoon (SPIM), several atmospheric general circulation models (AGCMS) that are used for generation seasonal monsoon predictions in India are evaluated. Compared to other models, the AGCM used by IITM (Portable Unified Model (PUM**)** from Hadley centre, UK) captures the spatial structure and year to year variability of monsoon reasonably well (Fig.6). Even then the prediction skill of this model is only 0.39. Thus, on the whole, the skill of the AGCMs in simulating the year-to-year variation of the ISMR and particularly the extremes is rather poor even when the SST is specified from observations. Also, local air-sea interactions over the warm pool are crucial for inter-annual variability of Indian monsoon rainfall (Wang et al. 2005). Hence, only atmospheric models are not reliable tool for predicting the monsoon rainfall.

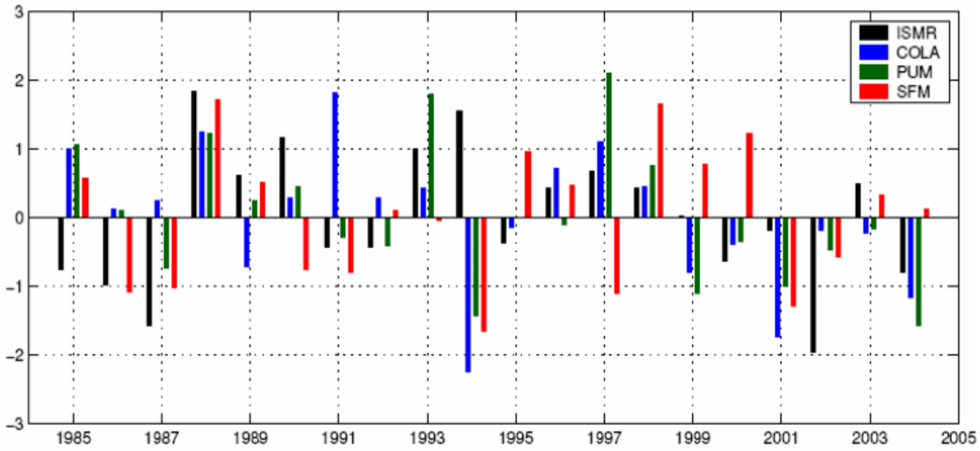


Fig. 6: Comparison between simulated ISMR rainfall departures by dynamical AGCMs and IMD observations (adopted from Srinivasan and Gadgil, 2011).

Fully coupled general circulation models (CGCM) seem to have somewhat better prediction skill compared to the standalone AGCMs and empirical models. Maximum prediction skill of about 0.43 (Fig.7) is achieved by National Centers for Environmental Prediction, Coupled Forecast System, (NCEP-CFS). **Even this CGCM is unable to reproduce the basic structure of monsoon reasonably well.** Hence, one of the steps could be to adopt one of such systems as base system for seasonal prediction on which development activity can be carried out for improving the prediction. NCEP-CFS could be the base system. The other option could be adoption of a multi-model ensemble prediction approach in which outputs of a number of models could be used which are available on operational basis.

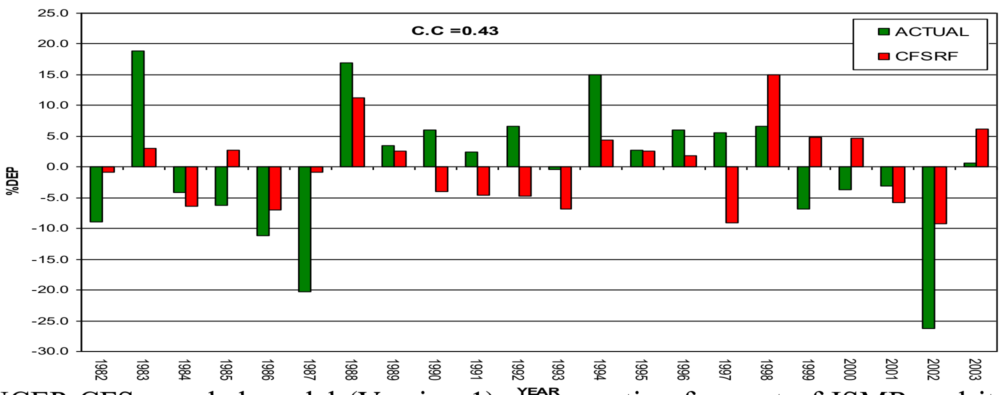


Fig. 7: NCEP-CFS coupled model (Version 1) retrospective forecast of ISMR and its comparison with IMD observations. Period : 1982-2003. May Initial Conditions. [Source : Dr. M. Rajeevan]

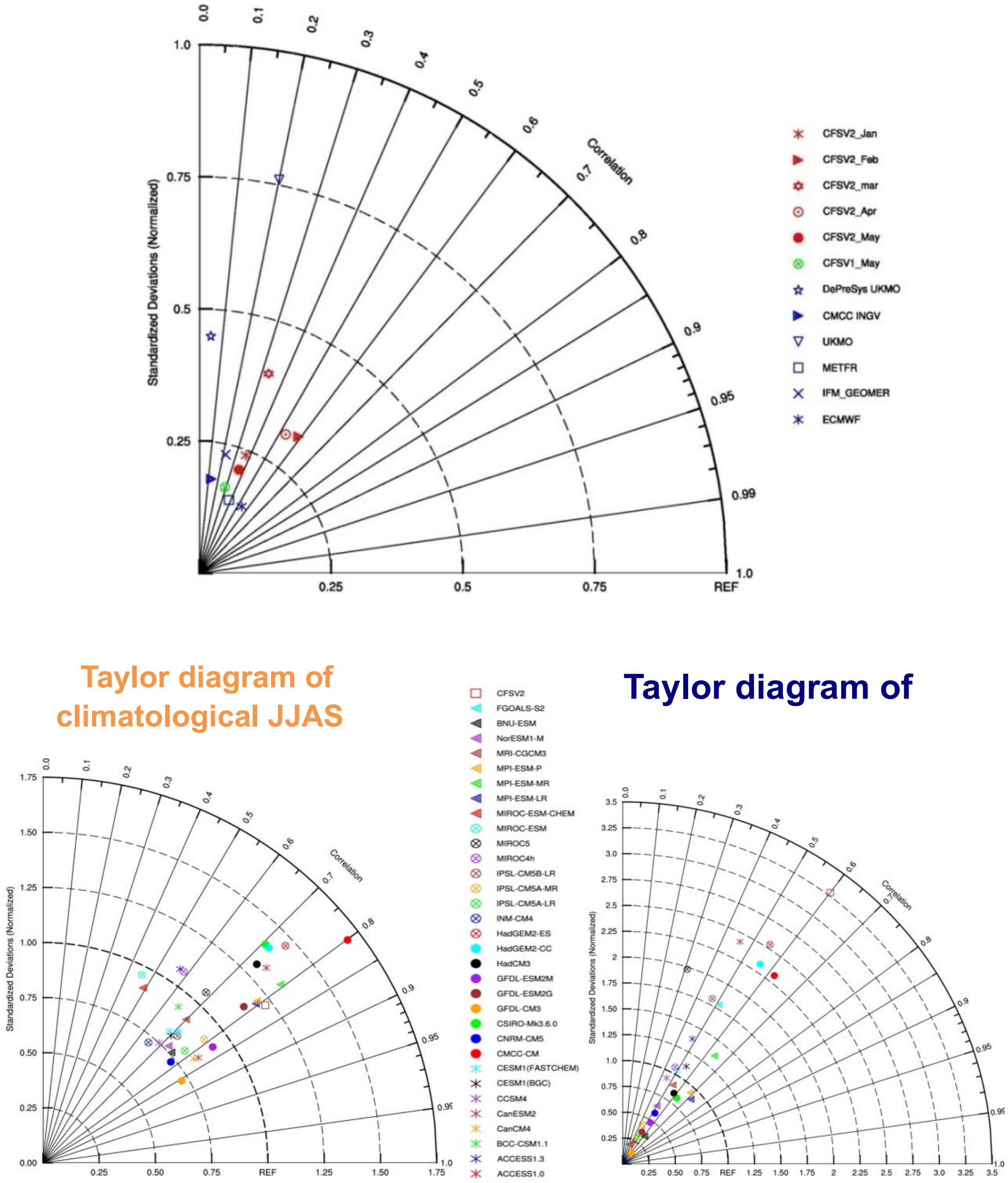


Fig. 8: Taylor plot of Monsoon rainfall prediction skill and normalized inter-annual standard deviation (with standard deviation of observed rainfall) over Indian land points from different coupled models participated in ENSEMBLES and CFS v1 and CFS v2 models (previous page). Taylor plot of Climatological JJAS mean precipitation averaged over the region (20°S- 30°N; 40°E-140°E) for CMIP5 models (lower left panel) and Taylor plot for MISO variance (lower right panel). Pentad CMAP data (1986-2005) are explored to compute the Taylor metric [Ref: Sabeerali et. al., 2013]

Taylor plot of Indian Summer Monsoon rainfall (ISMR) prediction skill is shown in Fig. 8. Red symbols indicate the CFS class models with different initial conditions. Clearly the CFS class models show better inter-annual variations compared to all other models except UKMO model. Though UKMO model captures better variance an seasonal time scale its prediction skill is limited and much lower compared to CFS model. At the same time, the prediction skill of Indian monsoon rainfall is better in CFS model compared to other models as well. Hence selection of NCEP CFS model for further development of monsoon prediction skill is justified. Table-1 shows the Pattern Correlation and Normalized Variance values of Climatological JJAS mean precipitation for different models. It may be noted that these values for CFSv2 are reasonably good.

Table – 1: Climatological JJAS mean precipitation

Models	Pattern Correlation	Normalized Variance
ACCESS1.0	0.75	1.33
ACCESS1.3	0.57	1.07
BCC-CSM1.1	0.65	0.93
CanCM4	0.82	0.82
CanESM2	0.82	0.84
CCSM4	0.69	0.75
CESM1(BGC)	0.70	0.81
CESM1(FASTCHEM)	0.69	0.82
CMCC-CM	0.80	1.69
CNRM-CM5	0.78	0.73
CSIRO-Mk3.6.0	0.71	1.40
GFDL-CM3	0.86	0.72
GFDL-ESM2G	0.78	1.14
GFDL-ESM2M	0.82	0.92
HadCM3	0.73	1.31
HadGEM2-CC	0.72	1.40
HadGEM2-ES	0.74	1.46
INM-CM4	0.65	0.72
IPSL-CM5A-LR	0.78	0.81
IPSL-CM5A-MR	0.79	0.91
IPSL-CM5B-LR	0.72	0.83
MIROC4h	0.59	1.07
MIROC5	0.68	1.06
MIROC-ESM	0.46	0.96
MIROC-ESM-CHEM	0.49	0.91
MPI-ESM-LR	0.79	1.19
MPI-ESM-MR	0.79	1.33
MPI-ESM-P	0.79	1.20
MRI-CGCM3	0.70	0.91
NorESM1-M	0.72	0.77
BNU-ESM	0.75	0.76

FGOALS-S2	0.71	0.84
CFSv2	**0.81**	**1.22**

Monsoon Intra-seasonal Oscillations in CFS model:

In a recent study, Sabeerali et al. (2013) have compared the CMIP5 simulations of monsoon intra-seasonal oscillations with simulations of NCEP CFS v2 model and found that seasonal mean rainfall simulations and monsoon intra-seasonal oscillation (MISO) simulations are reasonably captured in NCEP CFS v2 and its simulations are better than the simulations of many models in CMIP5 (Fig. 8: lower left panel for precipitation, lower right panel for MISO). Table-2 shows the Pattern Correlation and Normalized Variance values representing Spatial pattern of MISO variance for different models. It may be noted that these values for CFSv2 are reasonably good.

Table – 2: Spatial pattern of MISO variance.

Models	Pattern Correlation	Normalized Variance
ACCESS1.0	0.46	2.42
ACCESS1.3	0.48	1.38
BCC-CSM1.1	0.44	5.46
CanCM4	0.41	0.29
CanESM2	0.47	0.24
CCSM4	0.45	0.93
CESM1(BGC)	0.54	1.12
CESM1(FASTCHEM)	0.50	1.04
CMCC-CM	0.62	2.32
CNRM-CM5	0.53	0.58
CSIRO-Mk3.6.0	0.63	0.82
GFDL-CM3	0.62	0.14
GFDL-ESM2G	0.51	0.36
GFDL-ESM2M	0.55	0.48
HadCM3	0.58	0.84
HadGEM2-CC	0.56	2.33
HadGEM2-ES	0.55	2.54
INM-CM4	0.55	0.02

IPSL-CM5A-LR	0.51	0.30
IPSL-CM5A-MR	0.44	0.43
IPSL-CM5B-LR	0.47	1.81
MIROC4h	0.47	1.06
MIROC5	0.31	1.98
MIROC-ESM	0.28	0.20
MIROC-ESM-CHEM	0.32	0.20
MPI-ESM-LR	0.72	0.90
MPI-ESM-MR	0.64	1.36
MPI-ESM-P	0.68	0.94
MRI-CGCM3	0.53	0.90
NorESM1-M	0.50	0.65
BNU-ESM	0.62	0.34
FGOALS-S2	0.51	1.79
CFSv2	**0.60**	**3.28**

It is well known from previous studies that the monsoon intra-seasonal oscillations (MISO) propagate from south of the equator to Indian land mass (Sikka and Gadgil, 1980). This feature is also well simulated in CFSv2 (Fig. 9) and the propagation is comparable with (GPCP) observations (Saha et al., 2014).

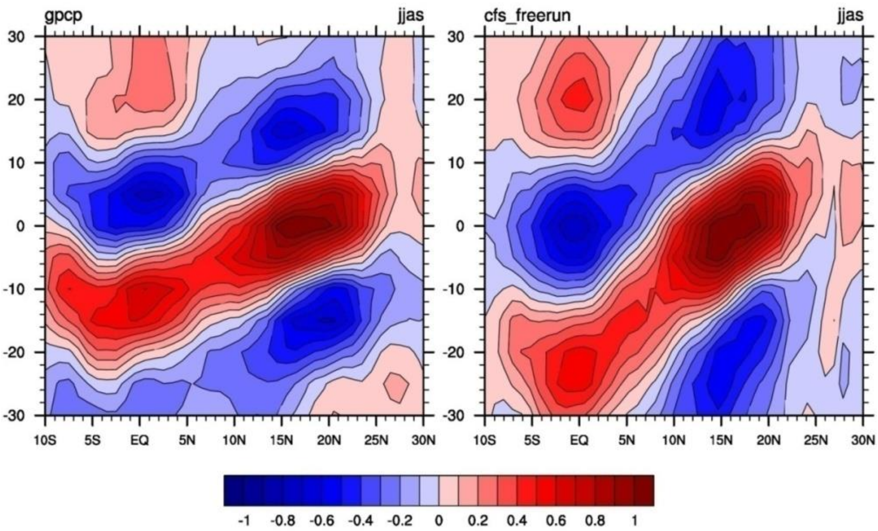


Fig. 9: Northward propagation of MISOs using lead/lag (days, in y-axis) regressed (20-100 day filtered) rainfall anomaly during JJAS (a) GPCP (b) CFS v2 (Saha et al., 2014)

Model Biases in CFS Model :

All CGCMs have some systematic biases. NCEP-CFS is not an exception. The mean ISMR is characterized by rainfall maxima over central India (CI) along with north Bay of Bengal (BoB), Western Ghat and south of equatorial Indian Ocean region (Fig. 10(c)). Both versions of CFS (v1 & v2) are able to simulate rainfall maxima over Western Ghat and north BoB (Fig.10(a) and (b)) ; however, there are large dry bias over CI. CFSv2 is able to simulate the Equatorial rainfall maxima; however, it is shifted towards west in CFSv1. Therefore, rainfall bias has east-west dipole structure in CFSv1 (Fig.10(d)). Chaudhari et al. (2013) have shown that this dipole structure of bias in CFSv1 has large implications in other related atmospheric processes through feedback mechanism. A dry (wet) rainfall bias over east (west) Indian Ocean induces anomalous low level easterlies over tropical Indian Ocean and causes cold SST bias over east Indian Ocean by triggering evaporation and warm SST bias over west Indian Ocean through advection of warm waters. The persistent SST bias retains the zonal asymmetric heating and meridional temperature gradient resulting in a circum-global subtropical westerly jet core, which in turn magnifies the mid-latitude disturbances and decreases the Mascarene high. The decreased Mascarene high diminishes the strength of monsoon cross-equatorial flow and results in less upwelling as compared to that in the observation. It further increases the SST bias over the West Indian Ocean (Chaudhari et al., 2013).

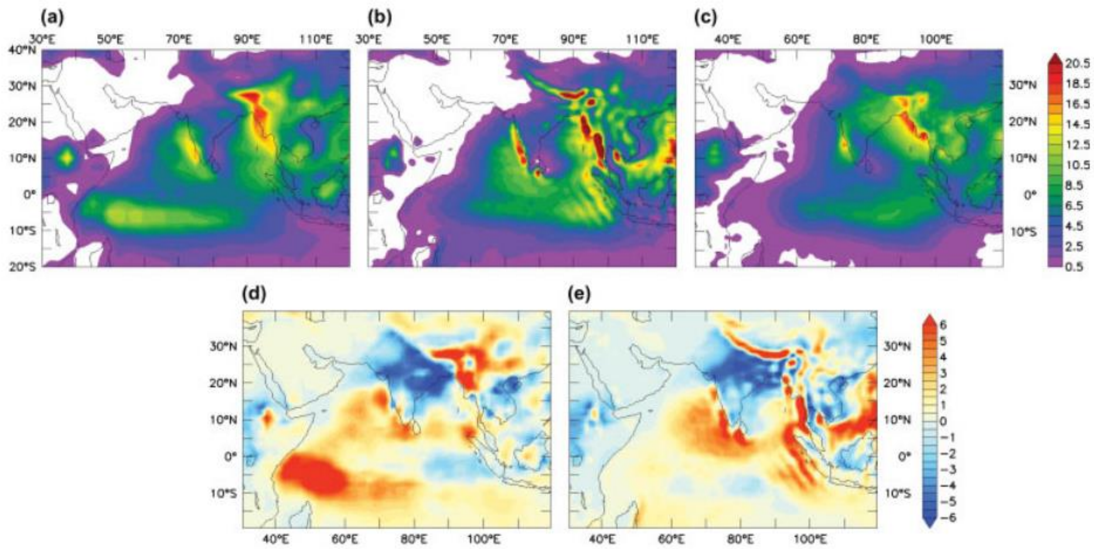


Fig. 10: Seasonal (JJAS) averaged Climatological mean rainfall (in mm/day) from (a) CFSv1, (b) CFSv2 and (c) GPCP. Biases (model-GPCP, in mm/day) in (d) CFSv1 and (e) CFSv2. (Saha et al., 2014)

The ability to simulate the right location of equatorial rainfall maxima is a major improvement in CFSv2 as compared with CFSv1 (Saha et al., 2014). Nevertheless the fundamental problem of dry bias over Indian land mass (CI) still persists and it is further enhanced in CFSv2 (Fig. 10(e)).

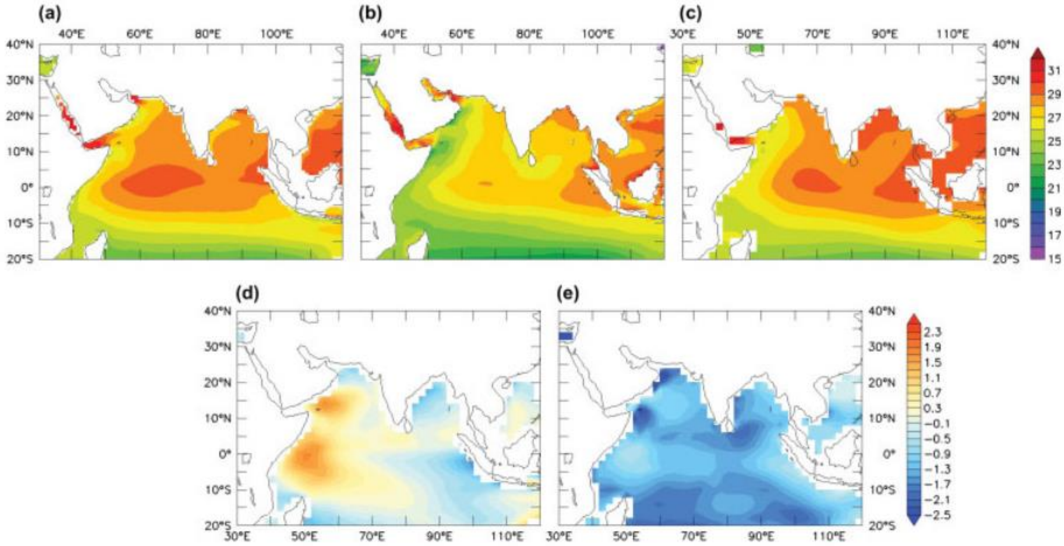


Fig. 11: Seasonal (JJAS) averaged Climatological mean SST (in °C) (a) CFSv1, (b) CFSv2 and (c) Reynolds SST. Biases (model - Reynolds SST) in (d) CFSv1 and (e) CFSv2 (in °C). (Saha et al., 2014)

The monsoon is a coupled ocean–atmosphere system and its strength is determined by air-sea interaction processes. SST, being an integral part of the ocean, plays a significant role in influencing ISMR. Realistic simulation of SST SST is one of the necessary conditions for better simulation of ISMR. The seasonal SST is characterized by warm pool region (SST > 28° C) over east Arabian Sea, entire BoB, central and eastern equatorial Indian Ocean is evident from Reynolds data (Fig. 11(c)). Both versions of the model are able to capture the spatial patterns of SST. However, the equatorial warm pool maxima is shifted towards west and there is a permanent east-west dipole structure in CFSv1 (Fig. 11(d)). On the other hand, CFSv2 underestimates SST over most of the Indian Ocean basin (Fig. 11(e)). Despite strong cold SST bias in CFSv2, rainfall pattern over BoB and equatorial Indian Ocean are reasonably good, which suggest, north-south SST gradient is more important rather than mean SST for the monsoon convective activity.

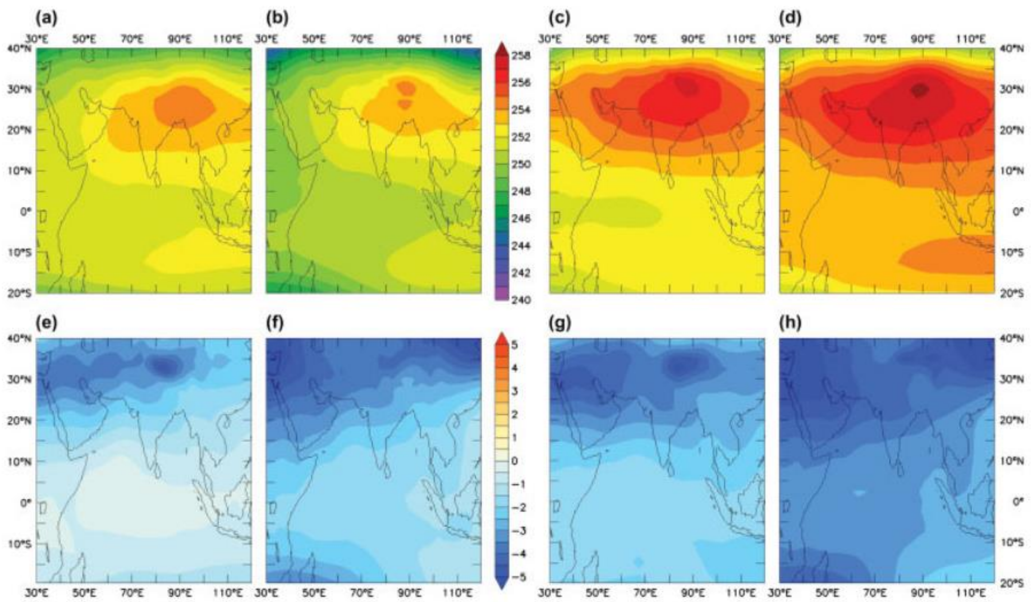


Fig. 12: Seasonal (JJAS) averaged Climatological mean tropospheric temperature (TT in °K). (a) CFSv1, (b) CFSv2 and (c) ERA– interim and (d) NCEP-II reanalysis. Biases (model-reanalysis) with

respect to ERA – interim (e) CFSv1-ERA, (f) CFSv2 -ERA , and with respect to NCEP-II (g) CFSv1-NCEP , (h) CFSv2-NCEP. (Saha et al., 2014)

North-south gradient of the vertically averaged air temperature between 200 hPa and 600 hPa (known as TT) over Indian subcontinent region is very important in order to sustain the monsoon circulation (Webster et al., 1998; Goswami and Xavier, 2005) . The meridional TT gradient (TTG) is also closely linked with the onset and withdrawal of Indian summer monsoon (Ueda and Yasunari, 1998; Goswami and Xavier, 2005). The north-south TTG is calculated using vertically averaged (200-600 hPa) temperature difference between a northern box (40°E - 100°E, 5°N-35° N) and the southern box (40°E - 100°E, 15°S-5° N) (Xavier et al., 2007). This TT is one of the most vital parameter which can be used to check the ability of a model for realistic representation of monsoon. Mean seasonal TT is dominated by elevated heat source of Tibetan plateau and a sharp meridional heating gradient, as large as 4-6°K, is seen in NCEP and ERA-Interim reanalysis (Fig. 12(c) and (d)). Both models are able to simulate the warm troposphere over Tibetan plateau along with the meridional temperature gradient (Fig. 12(a) and (b)). However, both models underestimate the mean TT as well as TTG (Fig. 12(e) and (h)). It may be noted that CFSv1 has more bias in TTG than that of CFSv2 (Figure not shown). Also, TT is underestimated throughout the Indian sub-continent region in both versions of the CFS model.

Cold bias in the temperature field may be attributed to the ill representation of the ratio of convective and stratiform rainfall (Saha et al., 2014). Observation shows that the ratio of convective and total rainfall over the tropical region is about 40–50%. However, in both models convective rainfall has major contribution (more than 90%) particularly over oceans. Although CFSv2 shows some slight improvements in CRF over Indian land-mass, it deteriorates over equatorial Indian Ocean. Monsoon onset and withdrawal dates are also more realistic in CFSv2 than that in CFSv1.

Other than improvements in mean seasonal fields, the intra-seasonal elements in terms of ISO variance and propagation characteristics are improved remarkably in the CFSv2. However, the speed of northward propagating ISOs are slower in both model and may be linked with the weak vertical shear in the zonal wind. Air–sea interaction expressed as a local SST and rainfall correlation is reasonably good in both versions of the model. Rainfall over Indian subcontinent is anti-correlated with Ni˜ no3 SST in a better way in CFSv2 as compared with CFSv1.

A preliminary result from the sensitivity experiment using OSU/NOAH land-surface models indicates the role of land-surface processes on the simulation of rainfall maxima over equatorial Indian Ocean along with maritime continent region (Saha et al., 2014). It is found that, CFSv2 using NOAH (OSU) land model produces more (less) rainfall over maritime continent region. This causes change in low-level westerly wind due to changes in the tropospheric heating, which in turn affects the SST over equatorial Indian Ocean. Therefore, some of the rainfall bias may be linked with the proper representation of land-surface processes and those need to be identified and improved. Apart from this, convective and stratiform rainfall ratio should be improved through the improvements in the cloud parametrization schemes. This can reduce the cold bias in the model. Further improvement in the simulation of mean monsoon is expected to increase prediction skill of CFSv2.

The above studies indicate that, there is lot of scope for improvement in seasonal prediction skill of monsoon rainfall in the CGCM, like NCEP-CFS.

5.2 Model Selection for Short and Medium Range Prediction (NCMRWF)

To adequately resolve the transient systems responsible for rainfall during monsoon and their movement, it is important to use models with high resolutions both in the horizontal and vertical. However, resolution is largely constrained by the available computing power. NCMRWF has attempted to use highest possible resolution models. In 2007, NCMRWF implemented a global Atmospheric General Circulation model (AGCM) of about 50 km resolution (T254) in horizontal and 64 levels in vertical. As the Centre acquired a new High Performance Computer (HPC) system, the horizontal resolution was increased to 35 km (T382L64) in May 2010 and subsequently the resolution was further increased to 22 km (T574L64) in June 2011. Under the MoU between MoES and UKMO, NCMRWF has implemented UKMO's Unified Model (UM) and associated 4D-Var Data Assimilation system. Currently UM at N512L70 (~25 km horizontal resolution at mid-latitude) along with 4D-Var is being operationally run in real-time. A regional version of the UM at 12 km resolution over the Indian monsoon region has been setup and is being tested for select cases. The performance of UM has been found to be slightly better than GFS in model evaluations during last few monsoon seasons (more details are found in Section 8.1 & 8.2). There are also plans to upgrade the global model resolution of UM to 16 km. The regional UM will be upgraded to 4 km and 1.5 km, where the physical processes like convection will be resolved explicitly.

5.2.1 Ensemble & Multi-model Ensemble Prediction System

The atmosphere is a chaotic system, and as a result, small errors in the initial conditions can grow to have a major impact on the subsequent forecasts. The true state of the atmosphere cannot be determined precisely due to observational errors, large data gaps and approximations in the analysis techniques. Therefore it is essential to provide estimates of the forecast uncertainty while carrying out medium range weather forecasts.

Ensemble prediction system involves integration of a numerical weather prediction (NWP) model a number of times, with slightly perturbed initial conditions, to assess the forecast uncertainty due to errors in the initial conditions and possibly in model formulation.

At NCMRWF, a 21 member Global Ensemble Forecast System using the T190L28 model (~70 km in horizontal) has been implemented recently. The initial perturbations are generated using Ensemble Transform with Rescaling (ETR) method (Wei et al., 2007). This system is currently used for generating probabilistic forecasts over Indian region.

NCMRWF is currently in the process of implementing a 44-member UM based global ensemble prediction system (at 33 km horizontal resolution and 70 levels in vertical and the same would become operational on the new HPCS this year. Subsequently a regional version of this ensemble system would be implemented which would be useful in predicting severe weather systems in the monsoon season. This ensemble system would also be used for implementing a hybrid ensemble 4D-Variational data assimilation at NCMRWF which would account for the "flow dependent errors of the day".

In recent years, major operational centres began making their forecast data available for exchange. This has led to the practical realization of another variant of Ensemble Prediction system - the Multi Model Ensemble (MME) forecasting system. In this method observations and forecasts of a variable from different models are used to build statistical relationships between them. Using these relationships and the forecasts from different models the final forecast values are computed. It is found that the method provides forecasts that have less RMSE than forecast from any individual system, in a specified sense. MoES has initiated a 'multi-model ensemble' (MME) forecasting project at NCMRWF. This MME is a joint activity of NCMRWF, IMD and IITM. Under this project monsoon rainfall forecasts in short and medium range have been made available for operational real time use for the Indian region. Initial results are encouraging. In Fig.6 the deviations of day-5 forecast against observed rainfall (analysis) during monsoon 2011 are shown. The multi-model ensemble forecasts have less error than the individual model forecasts.

5.3 Model Selection for Short and Medium Range Prediction and Work Plan (IMD/IITM)

The Global Forecast System GFS T382L64 (~ 35 km in horizontal over the tropics), adopted from National Centre for Environmental Prediction (NCEP), was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) in May 2010. Very recently in the year 2012, GFS T382 has been replaced by the upgraded version of the model GFS T574L64 (version GSM 9.1.0) (~ 25 km in horizontal over the tropics). Before this new version is made operational, in order to validate the performance skill, the model was operated in the experimental mode during the year 2011, in addition to the operational run of GFS T382. Real-time forecast products of both the models were made available to the national web site of IMD (www.imd.gov.in). We have documented (Durai and Roy Bhowmik, 2013) the performance statistics of GFS T574 against the performance statistics of GFS T382, on the basis of daily day-1 to day -7 forecasts generated during summer monsoon 2011 (1 June to 30 September).

Daily rainfall analysis generated at the resolution of 0.5^{o} from the use of daily rain gauge observations (IMD) and satellite (TRMM) derived quantitative precipitation estimates (QPE), obtained from NASA web site is used as the observed dataset for the validation purpose. The model outputs are used to prepare day to day operational forecasts for five days with outlook for subsequent two days to meet the requirement of public weather services and other user specific applications in the country. Model performance is evaluated for day-1 to day-5 forecasts of 24-h accumulated and seven days cumulative rainfall in terms of several accuracy and skill measures. Performance of the model is also examined in terms of vertically integrated moisture flux, precipitable water content, lower tropospheric wind circulations to understand the monsoon rainfall features captured by the model. The performance of the model during the episode of a monsoon depression is also illustrated in this study. Model performance statistics for upper air parameters of geopotential height, temperature and wind forecasts over different regions of the globe are also described.

In the operational mode, the Global Data Assimilation (GDAS) cycle runs 4 times a day (00 UTC, 06 UTC, 12 UTC and 18 UTC). The assimilation system (for GFS T574) is a global 3-dimensional variational technique, based on NCEP Grid Point Statistical Interpolation (GSI 3.0.0; Kleist et al 2009) scheme, which is the next generation of Spectral Statistical Interpolation (SSI; David et al 1999). The major changes incorporated in T574 GDAS compared to T382 GDAS are: use of variational quality control, flow dependent re-weighting of back ground statistics, use of new version and coefficient for community radiative transfer model, improved tropical cyclone relocation algorithm, changes in the land, snow and ice skin temperature and use of some new observations in the assimilation cycle. Statistics of daily data used in the assimilation during August 2012 is shown in Table-3. The various types of conventional and non-conventional data which are assimilated into the GFS T574/L64 are documented by Kotal and Roy Bhowmik (2013).

List of data presently being pre-processed for Global Forecast System at IMD are:

§Upper air sounding – TEMP, GPS & PILOT
§ Land surface – SYNOP, SYNOP MOBIL & AWS
§ Marine surface - SHIP
§ Drifting buoy - BUOY

§ Sub-surface buoy - BATHY
§ Aircraft observations - AIREP & AMDAR
§ Automated Aircraft Observation - BUFR (ACARS)
§ Airport Weather Observations - METAR
§ Satellite winds - SATOB
§ High density satellite winds - BUFR (EUMETSAT & Japan)
§ Wind profiler observations - BUFR (US/Europe)
§ Surface pressure Analysis - PAOB (Australia)
§ Radiance (AMSU-A, AMSU-B, HIRS-3 and HIRS-4, MSU, IASI, SSMI, AIRS, AMSRE, GOES, MHS)
§ GPS Radio occultation
§ Rain Rate (SSMI and TRMM)

The analysis and forecast for seven days are performed using the High Power Computing System (HPCS) installed in IMD Delhi. One GDAS cycle and seven days (day-1 to day -7) forecast at T382L64 (~ 35 km in horizontal over the tropics) takes about 30 minutes on IBM Power 6 (P6) machine using 20 nodes with seven tasks (seven processors) per node, while the same for GFS T574 (~ 25 km in horizontal over the tropics) is approximately 1 hour 40 minutes.

Table -3 : Statistics of daily data used in the assimilation during August 2012

Parameter	p surface	u, v	t	q	radiance
Total No. of daily data received	29339	40814	126947	51958	2982385
Total No. of data assimilated	25610	292369	101474	15367	744426
% of data accepted in the assimilation	87%	71%	79%	30%	29%

Chapter 6: Strategy for model development

6.1 The way forward:

To improve the prediction skill of monsoon rainfall in dynamical models, it is important to reduce the systematic bias of the models. The models with high fidelity will show a better prediction skill (Delsole and Shukla, 2010). Here fidelity refers to the degree to which the climatology of the hindcasts matches the observed climatology and skill refers to the degree to which individual hindcasts match individual verifications. In general models with poor climatologies are expected to have poor skill. Therefore, the main strategy should be to improve the fidelity of the models by various methods like improving physical parameterizations, better ocean initialization, incorporating land-atmosphere coupling and better data assimilation methods.

At a fundamental level, models have systematic biases (errors) in three areas:

(i) In simulating the space-time spectra of tropical clouds, specially during northern summer. This problem can be largely identified as inability to simulate the summer monsoon intra-seasonal oscillation (MISO)
(ii) net heating profile (proportion of stratiform to convective clouds). Most models have serious bias in simulating the observed proportion of convective and stratiform precipitation, and
(iii)the phase of diurnal cycle.

These three aspects can be achieved by the following means.

High resolution Modelling: It is believed by many researchers that increasing resolution of the models it is possible to simulate the space-time spectra of tropical clouds and possibly increase the prediction skill of the models. Some even go to the extent that global cloud resolving models may be required (Shukla et al. 2009). This is certainly a direction to be explored. To a certain extent increasing resolution of the coupled model will enhance the prediction skill of the model (see Table - 4), however, beyond some point it is unlikely that the prediction skill will be further improved. For example, the 20-km global model of MRI still fails to simulate the MJO correctly (Rajendran et al. 2008).

Correlation Coefficients of JJA Monsoon Indices

Corr. Coeff. (1981-2006)	T62	T126	T382
MHI	0.19	0.15	0.23
IMI	0.03	0.24	**0.39**
WYI	**0.45**	**0.35**	0.30
WNPMI	**0.76**	**0.68**	**0.58**
EASMI	0.24	**0.34**	0.11
RM2	0.15	0.20	0.15
AUSMI	0.17	- 0.08	0.22

90% 95% 99%

Table - 4: Correlation coefficients between predicted and observed JJA monsoon indices in CFS CGCM at different resolutions. (MHI: Monsoon Hadley Circulation index, IMI: Indian Monsoon Index, WYI: Webster-Yang index, WNPMI: Western North Pacific Monsoon Index, EASMI: East Asian Summer Monsoon Index, RM2: Regional Monsoon Circulation Index, AUSMI: Australian Summer Monsoon Index) [Source : IMD]

6.1.1 In recent times, a new concept **"Super Parameterization"** is evolving in which a coarse resolution AGCM is coupled with a cloud system resolving model. In this model space-time spectra of rainfall is much better resolved compared to AGCM of similar resolution. In general, a GCM that uses super parameterization is three times more CPU intensive than an AGCM that uses conventional parameterization schemes. It appears to be one of the promising areas of research to improve seasonal monsoon prediction.

6.1.2 Most of the Convective parameterization schemes, which are in use in weather and climate models, have been developed based on few detailed field campaigns such as the GATE. However, within the tropics, the interaction between small scale clouds and large scale environment may vary significantly due to local conditions (e.g., orography and land-sea contrast). Also, the role of aerosols have not been fully accounted in these parameterizations. It is not yet understood, whether same parameterization schemes are applicable over Indian monsoon region. Observational campaigns are already started by MOES/IITM to address this issue. Similar **observational campaigns are also required to enhance the understanding of land surface processes and ocean mixing parameterization schemes**.

6.1.3 Recent studies have shown that assimilation of subsurface ocean data and using the assimilated data in a coupled general circulation model significantly enhance the prediction skill of weather. **Research in similar direction in land surface data assimilation** is very much essential to improve the prediction skill of the monsoon rainfall.

6.1.4 Ocean plays a very important role in prediction of weather and climate by providing the required memory to the atmosphere. Many of the ocean models are unable to simulate the SST and mixed layer temperature reasonably and thermocline in the models is too diffused due to unresolved physics and deficiency of accuracy in forcing fields. Hence, a parallel approach is required to improve the ocean model parametrization schemes, particularly the mixing (both horizontal and vertical) by carrying out intensive observational campaigns with a focus on improving the parametrization schemes in the ocean models.

Climate Forecasting System (CFS) model developed by National Center for Environmental Prediction (NCEP) of USA is reasonably better compared to other coupled models in predicting the monsoon rainfall (Fig. 8). This model is already available to Indian Institute of Tropical Meteorology (IITM, Pune) and successfully running on their high performance computers. Prediction skill of this model, even at T62 normal resolution of AGCM, is above 0.4 and hence, it is proposed to use this model for further development to improve the prediction skill of Indian summer monsoon rainfall. All groups that get involved in this mission should use this model (or components of this model) for development and research activities, so that concerted efforts of different groups will result in a better tool for monsoon prediction.

6.1.5 Short and Medium Range Prediction (NCMRWF):

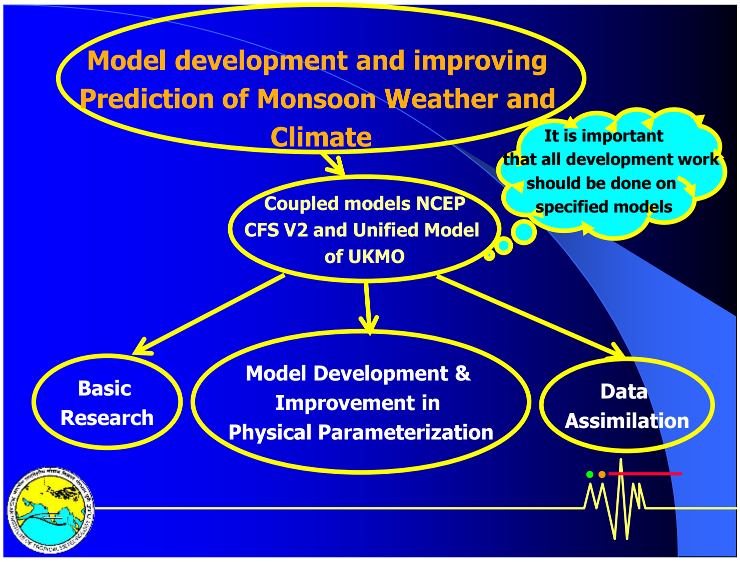
All current operational NWP systems/models have limitations in predicting anomalous monsoon features, particularly the extreme events like heavy rainfall. In view of limited skilled manpower resources available in the country, a view is emerging that to begin with the best possible model, from among those that are available, should be chosen. Then concerted efforts in a synergetic fashion should be put to further improve its performance over Indian monsoon region. The following is proposed as guideline for it:

- present performance
- better technology (e.g. 4D-VAR; Land Surface Assimilation etc.)
- active involvement of large number of interested groups in system development
- collaboration in areas of mutual interest
- better documentation
- software design/technology permitting large, diverse groups to work in parallel

The experience at NCMRWF shows that unified model of UKMO is most suitable (Please see Section 8.2) for the details on the performance of UM). It captures monsoon synoptic features well. Over monsoon region, its performance over short and medium range is consistently better than the system presently operational at NCMRWF and also that of NCEP, JMA etc. It uses 4-D VAR assimilation system which extracts more information from observations consistently, in a better way. A large number of centres (Australia, New Zealand, South Korea, South Africa, and Norway) have started using this system.

There are also plans to upgrade the global model resolution of UM to 16 km. The regional UM will be upgraded to 4 km and 1.5 km, where the physical processes like convection will be resolved explicitly. NCMRWF is currently in the process of implementing a 44-member UM based global ensemble prediction system at 33 km horizontal resolution and 70 levels in vertical and the same would become operational on the new HPCS. Subsequently a regional version of this ensemble system would be implemented which would be useful in predicting severe weather systems in the monsoon season. This ensemble system would also be used for implementing hybrid ensemble 4D-Variational data assimilation at NCMRWF which would account for the “flow dependent errors of the day”.

In general, the following strategy is proposed.



Under this mission, it is proposed to

(i) encourage research efforts by national and international research groups in the above mentioned areas of interest. Support could be rendered to the International community through funding on case to case basis.
(ii) support observational programs that will result in better understanding of the processes that will in turn result in improving the parameterization schemes in AGCMs, OGCMs, and land surface models.

In each of these areas, some important questions to be addressed are summarized below:

(a) Dynamics of Monsoon IAV.
(b) What makes each year monsoon different
(c) What are the combination of driving forces that makes each monsoon different
(d) Basic understanding of tropical clouds, its parameterization & representation of diurnal cycle
(e) Realistic representation of various scale interactions at various time scales

6.2 Proposed modalities to achieve mission objectives:

- ESSO-IITM is given responsibility to coordinate and execute the Monsoon Mission activities by setting up Monsoon Mission Directorate.
- ESSO-IITM will coordinate the work on model development and improvement for seasonal and extended range prediction.
- ESSO-NCMRWF will coordinate the work on model development and improvement for short to medium range forecasts.
- It is proposed to announce a Research Opportunity through which proposals will be invited from National Institutes as well as international Institutes on very specific projects through which improvement of the CFS/UKMO model could be achieved towards better forecasts of monsoon. ESSO-IITM will coordinate this activity in calling the proposals, evaluating them, awarding the projects and monitoring of the progress of the work.
- Proposals will be formulated so that they are directly relevant in improving the forecast of the CFS/UKMO model system
- Certain amount of funding for the National partners as well as the international partners will be year marked

- The Proposal partners from India will be allowed to use the HPC facility at ESSO-IITM which will be suitably enhanced for this purpose.
- Funding for students, post docs and some scientists time (consultancy) and some minor equipments may be provided.

6.3 Need for Enhanced Computing Infrastructure

In recent years there has been a dramatic enhancement of computing power in the new generation machines. ESSO-MoES has acquired 3 state of the art High Performance Computing machines to conduct its operational and Research activities. MoES Institutes has access to 15 Teraflop machines for its operational NWP activities and R & D activities to run global and regional forecast models for Short to Medium range and extended to long range prediction.

Concurrently, the International community has been active in collecting data from atmosphere over land and ocean areas and from the ocean depths and surfaces too by deploying Buoys, Floats and specialized diving sensors called Argo etc. The Land surface processes controlling surface flux of water vapour and energy are also being monitored. Along with this, the data available from the ongoing Modernization Program of IMD will help in improving performance of Coupled Models for seasonal and climate forecasting. India needs to undertake this task by adding infrastructure beyond its medium range needs. Machines of Peta flop range and large volume data handling systems will be required along with necessary human resource development and capacity building.

Chapter 7: Work Plan for Model development

7.1 Identifying the Model Biases

Efforts will be made to identify the model biases in both free runs and hindcast runs for both the coupled modelling systems (NCEP CFS and UKMO UM). The reasons behind the growth of these model biases (errors) will be investigated and probable sensitivity experiments will be carried out to reduce these errors. Some of the studies (at IITM) related to identification of model biases has already been mentioned in Section 5.1. The models which show fidelity in mean monsoon circulation are expected to perform better in real time monsoon prediction.

7.2 Improvements to Model Physics

7.2.1 Cloud-Cumulus parameterization in CFS to improve prediction of Indian Summer Monsoon

Arakawa (2004) gave a detailed review of the conceptual framework of current cumulus parameterization and mentioned about the limitations. Arakawa (1975) mentioned that clouds and associated microphysical processes affect the climate system through the coupled radiative-dynamical-hydrological processes in terms of release of latent heat of condensation, evaporation etc. and redistribution of latent and sensible heat in the atmosphere. There are other important processes related to Ocean and Planetary Boundary Layer (PBL) as well. Cumulus convection plays an important role in the mentioned coupled processes. Therefore representation of cumulus convection or cumulus parameterization in numerical model is one of the most important component that can affect the model simulation. Much of the model uncertainties is attributed to the inappropriate representation of clouds and associated processes. Major practical and conceptual problems in the conventional approach of cumulus parameterization, includes inappropriate separations of processes and scales (Arakawa, 2004). The 41 intermodal variance of projections of ISMR (Indian Summer Monsoon Rainfall) by the models in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) is as large as the signal of increase in the ensemble means (Randall et al. 2007). Among a few other reasons, a major reason for the current suite of climate models' poor skill in predicting the seasonal mean ISMR and uncertainty in the projections under climate change scenarios is the large systematic dry bias over the Bay of Bengal (Randall et al. 2007).

Keeping the above studies in to account and the present performance of cumulus parameterization, a suite of approaches are planned to be implemented in the CFS Version2 model for the purpose of improving the ISMR.

The studies based on observations (Abhik et al. 2012, Chattopadhyay et al. 2009, Goswami et al., 2011, Jiang et al., 2011) gave a framework to understand different mechanisms related to dynamics and cloud processes during different phases of ISMR. The hypothesis put forward for the mechanism which is responsible for evolution of different ISMR phases could be actually tested in a coupled model such as CFSV2 provided the necessary representation of cloud processes are implemented.

As such with this background motivation and objectives we have proposed to implement following developmental work in CFSV2

1. To develop a Multiscale Modelling Framework or Super parameterized CFSV2 where several Cloud Resolving Models will be inserted in each CFS grid to explicitly compute the tendencies of cloud hydrometeors and the heating contribution which then would be fed back to the CFS. A schematic of the SP-CFS framework is shown in Fig. 13.
2. To adopt a microphysical parameterization which has the ability to compute the tendencies of all the observed hydrometeors namely cloud water, cloud ice, graupel, snow, rain to test whether the space-time distribution of the condensate would modify the vertical heating profile of the model and in turn would influence the divergence-convergence in the upper and lower atmosphere. Finally to change the space-time distribution of ISMR.
3. Another approach would be to develop a Stochastic multiscale multicloud parameterization within CFSV2. The present day cloud-convective parameterizations are deterministic type. Keeping in mind the inherently nonlinear and chaotic nature of atmospheric processes, a stochastic approach will be attempted (Majda et al. 2011).

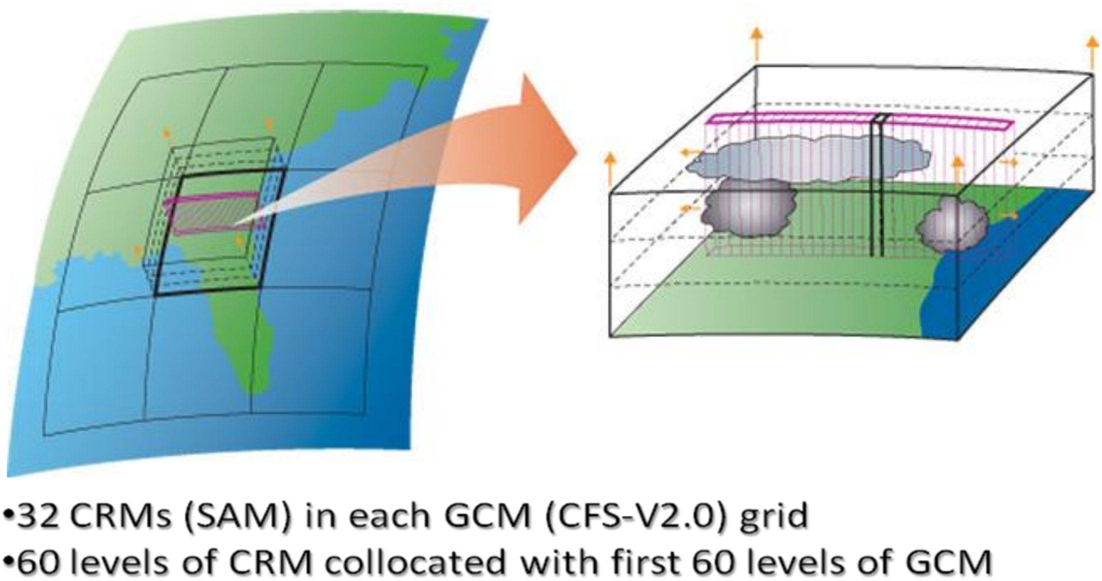


Fig.13: Schematic representation of Super Parameterization

7.2.2 Microphysical processes in operational General Circulation Model

Quantitative forecasting of precipitation has been one of the major challenges in operational General Circulation Model (GCM). Besides other processes, understanding of microphysical process is one of the key aspects in GCM. The effects of clouds on the treatment of condensation and evaporation are also important in the precipitation calculation. Although using simple scheme some reasonable precipitation forecasts have been produced but one cannot neglect cloud water and cloud ice in the model thermodynamic and hydrological fields. Furthermore, the exclusion of ice-phase clouds in the model can lead to underestimates of latent heat released above the freezing level and therefore weakens the feedback of condensation to the thermodynamic fields. Recently Waliser et al. (2009) have shown that the representation of cloud ice in GCM is inadequate. They have analyzed many satellite data and pointed out that even though parameterization in GCMs accounting for cloud ice processes have, still is not sufficient. A schematic diagram illustrating measurement methods for estimating cloud ice water content/path, including in-situ measurements as well as passive, radar and limb-sounding satellite techniques have been shown in Fig. 14.

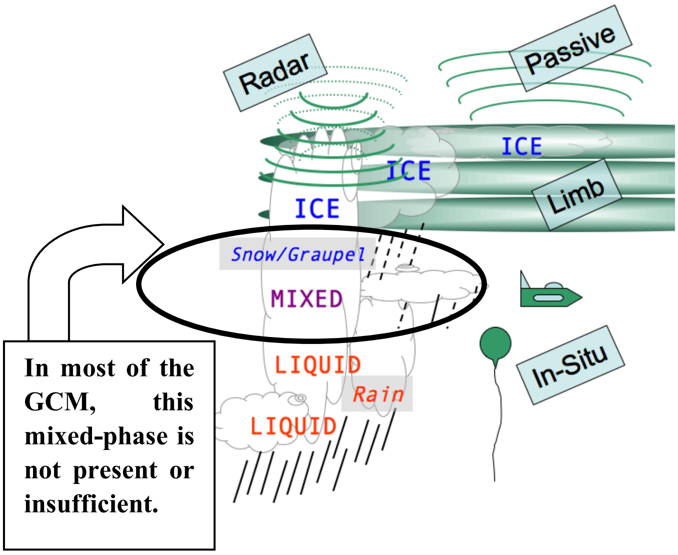


Fig. 14: Schematic diagram illustrating measurement methods for estimating cloud ice water content/path, including in-situ measurements as well as passive, radar and limb-sounding satellite techniques.

(Adopted from Waliser et al. 2009)

The parameterization of precipitation production is required in order to water substance from the atmosphere to the ground. The difficulties in the precipitation calculation arise from the complexity of the precipitation formation processes that involves complicated interactions among precipitation particles of different size, shape and phases. A complete description of precipitation formation required a good understanding of the characteristics and behavior of the different hydrometeors in the atmosphere. Understanding the representation of some processes like auto-conversion and accretion in the warm phase, aggregation and the Bergeron process in the mixed phase of the GCM are also essential. The cloud ice growth processes are associated with ice mass and/or particle diameter and also particle fall velocity. The deposition is the primary process associated with cloud and snow, while riming is the primary processes responsible for graupel formation (Fig. 15).

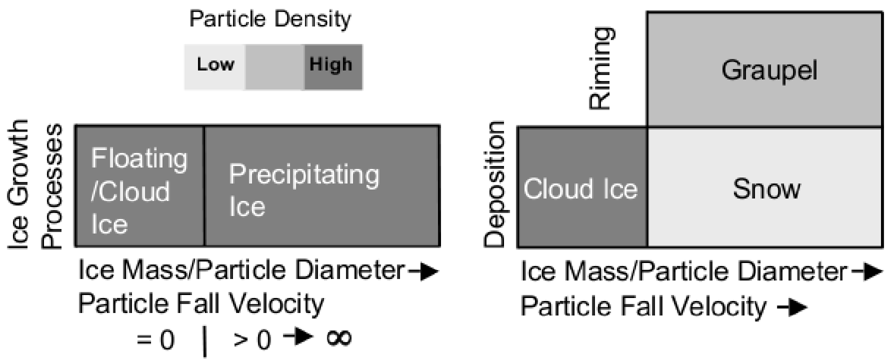


Fig. 15: Schematic diagram illustrating basic features of model parameterizations of cloud-related ice for a conventional GCM using a single species microphysics scheme (left) and a 3-species microphysics scheme (right). (Adopted from Waliser et al. 2009)

The biases in GCM representations of clouds – initially ice and liquid water content profiles (CIWC and CLWC) and integrated paths (CIWP and CLWP), with more recent efforts involved in exploring and quantifying the radiative impacts of precipitation – which is often ignored in GCMs.

Additionally, cloud-aerosol interaction and the role of cloud condensation nuclei (CCN) and ice nuclei (IN) of various species (e.g., mineral dust, soot, bio-aerosols) (Chen et al. 2008, Hoose et al. 2010) are important for the cloud ice and mixed-phase cloud formation. To perform a realistic model simulation, one needs to know not only microphysical mechanisms involved but also the properties (i.e. ice nucleation capabilities) of IN species.

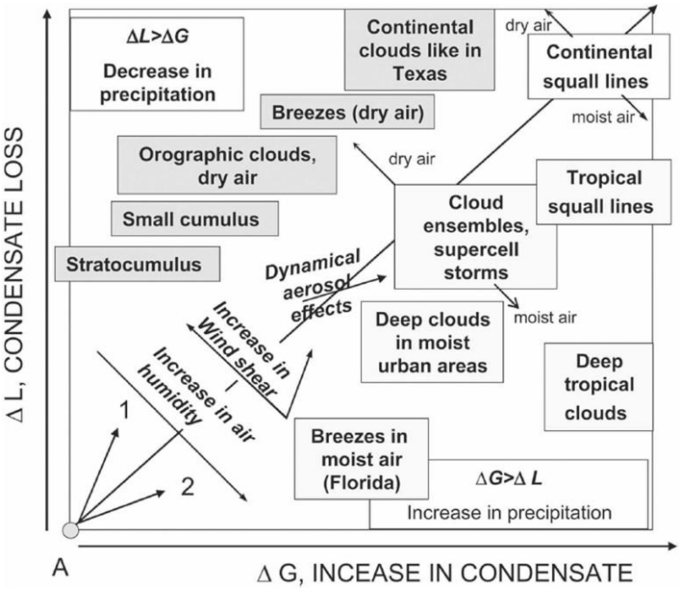


Fig. 16: A schematic diagram of aerosol effects on clouds and cloud systems of different types. The zone above the diagonal corresponds to a decrease in precipitation with aerosol concentration. The zone below the diagonal corresponds to an increase in precipitation with an increase in the aerosol particle concentration.

(Adapted from Khain et al., 2008)

Thus, the objective of this work is to evaluate the response of microphysical processes in operational GCM where cloud water and cloud ice are prognostically calculated. Since we wish to progress model's quantitative precipitation forecasts by improving microphysical processes although these processes are complex enough associated with precipitation.

7.2.3 Land Surface Processes:

There is ample evidence that dynamical coupled models of the Earth's climate system are reasonably good sources of seasonal predictions of the Indian monsoon and that the Climate Forecast System, version 2 of the U.S. National Centers for Environmental Prediction is arguably among the best such models for predicting climate fluctuations on seasonal to inter-annual time scales. There is also evidence that the Indian monsoon is more predictable in theory than can be achieved with current prediction models. There are many sources of this predictability, including the influence of long-lived sea surface temperature anomalies in the tropical Pacific and Indian Oceans and of the soil moisture anomalies in Eurasia that act to alter the circulation and thermodynamic forcing of the atmosphere in the vicinity of south Asia, thereby influencing the precipitation over India during the Asian summer monsoon season. Complex land-atmosphere and ocean-atmosphere interactions, as well as complex interactions of the atmospheric circulation in different regions, all contribute to predictability as well, which is one reason that dynamical models produce predictions that are superior to those obtainable from empirical methods. The gap between the level of predictability and actual prediction skill for the Indian monsoon can be attributed to either poor representation of relevant processes in the prediction model, poor representation of relevant features of the initial state, or both. In the proposed work, we will examine several potential sources of the prediction skill gap arising from both poor model formulation and poor initialization. Because the "memory" of the atmospheric state is limited to less than two weeks

Skill of seasonal monsoon forecasts depends on the atmospheric response to slowly varying states of the components of the Earth system, which can be predicted weeks to months in advance. ENSO is the most famous coupled atmosphere ocean mode, which modulates the Indian summer monsoon through its slowly varying cycle (i.e. El Nino, La Nina) . Another important slowly varying component of the Earth system is soil moisture, which can influence weather and climate through its impact on evaporation and surface energy fluxes. Land atmosphere interactions have been recognized as one of the important sources of monsoon variability in many past studies (e.g. Shukla and Mintz , 1982; Webster , 1983; Meehl , 1997; Ferranti et al., 1999; Koster et al., 2004; Takata et al., 2009; Saha et al., 2011, 2012). However, there are very few measurements of land surface parameters, which restrict our ability to demonstrate impact of land surface on the seasonal monsoon rainfall. Many climate models have demonstration impact of soil moisture on rainfall and have raised hope for further improvements of land surface processes and their feedback with atmosphere, which eventually may lead to improvement in the seasonal forecast of Indian summer monsoon. The following tasks are planned to improve the land surface processes, their interactions and hence the monsoon simulation by CFSv2.

1) Analyze climate simulations by CFSv2 (free run) and identify major biases in the model and possible link with the land surface processes.
2) Perform simulation using standalone land surface model (LSM), which is used in CFSv2 (i.e., NOAH) using observed/reanalysis meteorological forcing. (undergoing)
3) Compare the standalone LSM simulation using available observations and find out the nature of biases (i.e. whether same as in CFSv2 or different).
4) Incorporate more realistic physical based scheme (which are also important for the monsoon) into LSM to improve biases identified in step 3 and then go to step 2. Cycle 24 will continue until there are reasonable improvements.
5) Incorporate and test the improved LSM in CFSv2, i.e. go to step 1.

CFS show strong dry bias over north and central India during monsoon season. Also the model simulated mean winter and spring snow over Eurasia is almost twice to that of the observation. It is shown that improvement in the winter/spring snow bias may improve the mean dry bias over north and central India (manuscript under revision). Step 2 is now undergoing. Some improvements are expected through first cycle of this work plan (i.e., 15) and within the time frame of this program. However, this cycle has to be continued for further developments along with the improved schemes in other components of the model (i.e. ocean and atmosphere).

7. 2. 4 Radiation Budget and Monsoon.

It is generally accepted that to the first order approximation, the differential heating between the ocean and land areas over the Indian subcontinent is a major factor in the creation of the monsoon circulation (Ramage, pg. 8, 1971). The estimate of the magnitudes of the actual heat budget components from various earlier studies brings out several factors impacting this heat budget. A popular figure of these source and sink terms established for the earth-atmosphere system are shown in Fig.1. The heat budget of an atmospheric system such as the Indian monsoon, ignoring horizontal and vertical transport, consists of balancing the effects of shortwave radiative and condensational heating with the effects of longwave radiative and evaporative cooling. Heat transfer in the atmosphere occurs in three ways: conduction, convection and radiation. The conduction requires actual contact between the mediums involved in the energy exchange, and air being a poor conductor of heat; it has a limited impact on the vertical exchanges of energy through layers of the atmosphere. However for a homogeneous fluid like the atmosphere, both convection and radiation are important mechanisms in redistributing heat vertically in the atmosphere. If we consider the monsoon region as a closed system (or a box) and ignore advection from outside the system, solar radiation is the only incoming energy source. Within this box, the radiation interact with the constituents (atmospheric gases, clouds, aerosols, water vapor, green house gases, the earth's surface to name few) that results in the creation of various types of internal heat source and sinks that transfer energy occurring at all spatial and temporal scales. Thus, knowledge of the radiation budget with the proper characterization of the heat sources and sinks is important in understanding the monsoon flow by giving one a feeling for the energy available for these motions. The estimation of the correct magnitude of heating and cooling is also important to improve the simulation of the radiation process and their feedback to the monsoon flow those are parameterized in the current state-of-the-art dynamical models used in monsoon forecast (e.g. CFS).

Several quantitative studies in the past decades starting from MONEX (1979) has been undertaken to improve the understanding of the internal irradiative processes as described in last paragraph from observations as well as models. The recent observational as well as modeling aspects include quantification of the impact on monsoon regional heat sources and sinks due to: aerosol chemistry (Roeckner et al. (1999); Chung et al. (2002); Menon et al. (2002); Chakraborty et al. (2004); Ramanathan et al. (2005); Lau et al. (2006); Bollasina et al. (2008); Collier and Zhang (2009); Zhang et al. (2009); Sajani et al., 2012), greenhouse gas chemistry as well as impact of pollutants (Meehl and Washington 1993; Lal et al., 1998; Meehl et al., 2003; Hu et al. 2000; May 2002; 2004; Meehl and Arblaster 2003; Fan et al., 2010), variability of water vapor and ozone-photochemistry (shine et al., 1999; Londhe et al., 2005; Randel and Park., 2007; Park et al., 2007; Kunze et al., 2010, cloud radiative effects, surface-heat fluxes from ocean and heating due to the elevated Tibetan Plateau.

7.3 Data Assimilation

Another major challenge is to exploit new data sources, primarily satellite data. As the volume of meteorological observational data generated is witnessing explosive growth, even timely reception of these observations, their processing, quality checks and ultimately their assimilation to generate consistent model initial state minimizing the uncertainties is a huge challenge. Development of robust online data monitoring system capable of producing quick data diagnostics poses great challenge. The future assimilation systems should be capable of assimilating voluminous non-conventional data from satellites(radiances/products), radars, automatic weather stations(AWSs) at more frequent intervals, say one hour (the current assimilation cycle is 6 hours). These in turn pose challenges of computing resources, storage, data flow bandwidth, expertise for developing, new, efficient data assimilation algorithms etc. Recently, major global NWP Centres (ECMWF, UKMO, Meteo-France, Canada Met Service, BoM Australia, NCMRWF) have started using 4-D variational assimilation, Kalman filters, Ensemble assimilation systems etc. and have shown significant improvement in accuracy of prediction over extra-tropics but there is clearly an urgent need for developing new techniques of data assimilation.

Experiments with a simple coupled ocean-atmosphere model (Singleton, 2011) show that the best forecasting results for weather and climate timescales are obtained with advanced **coupled** data assimilation, using either 4D-Var or EnKF. LETKF is efficient and simple to couple, but coupled assimilation using 4D-Var is essentially unfeasible because it is computationally too expensive and complicated. For the real monsoon system, improving weather and climate prediction also requires the use of advanced coupled atmosphere-land-ocean data assimilation, which is made possible by the use of an efficient EnKF like the LETKF.

7.4 Verification Strategy

7.4.1 Verification Strategy for Seasonal and Extended Range Prediction

Deterministic forecasts provide a single expected value for the forecast variable. Probabilistic forecast provides probabilities of occurrences or non-occurrences of an event or a set of fully inclusive events. The events can be also classified into categories (above/below normal or above/near/below normal for example). Although equi-probable categories are preferred for consistency, other classifications can be used in a similar fashion. The most commonly used equal groupings are terciles, which are three ranges, or intervals, of values of a variable (e.g. rainfall or temperature) that are defined to describe the lower, middle, and upper thirds of the climatologically expected distribution of values. ESSO-IMD uses 5-categories of rainfall that are not equal groupings to describe the all India season (June-September) rainfall.

7.4.1.1 Parameters to be verified

At present the extended range and seasonal forecasts are being prepared/issued for the following two parameters. We recommend that these two parameters may be rigorously verified against observations.

a) Rainfall amount/anomaly

b) Sea surface temperature (SST) anomaly

7.4.1.2 Verification Strategy

The operational rainfall forecasts of ESSO-IMD are based on statistical models and are one dimensional (time series of area averaged rainfall). On the other hand, the experimental forecasts being generated by ESSO-IITM are based on dynamical models and the rainfall and SST forecasts are two-dimensional. Therefore, the verification strategy for the forecasts of ESSO-IMD and ESSO-IITM needs to be different.

For verification of dynamical model based hindcasts/forecasts, the following strategy is recommended. The strategy is to verify area averaged and large scale performance.

(a) Seasonal/monthly precipitation anomaly averaged over
  a. a larger domain, the south Asian monsoon region (0 – 400N, 500E-1200E)

  b. Indian main land region including north-east India (grid points covering all the Indian land mass), which is the same for the ESSO-IMD's seasonal forecasts and

  c. four large geographical regions of the country as defined by ESSO-IMD

(b) Sea surface temperature (SST) anomaly averaged over the Niño3.4 and the Indian Ocean Dipole Index. For the JJAS period, Indian Ocean Dipole index is not a proper measure. Therefore, SST anomalies from the eastern box may be considered for verification during JJAS period.

(c) Large scale aggregated overall measures of rainfall forecast performance at grid points over

  a. South Asian monsoon region (0-40N, 50E-120E)

  b. Indian main land region

  c. four large geographical regions of the country as defined by IMD

This item is different from the item (a), as this verification is done on each grid point and then aggregating, while the item (a) is done on an area averaged quantity.

(d) Large scale aggregated overall measures of SST anomaly forecast performance at grid points over
  a. Tropics (300S-300N, 0-3600E)

  b. Indian Ocean (250S -250N, 500E-1200E), and

  c. Tropical Pacific (250S-250N, 1200E-900W)

(e) Large scale monsoon index such as Monsoon Hadley Index (meridional wind difference between 850 hPa and 200 hPa over a broader region 100-300N, 700E-1100E).

(f) Tropospheric temperature gradient index (vertically integrated temperature difference between 200 and 600 hPa between a north box (10-35N, 30-100E) and south box (15S-10N, 30-100E)).

Large scale verification statistics (c and d above) are required to evaluate the overall skill of the models and ultimately for assessing its improvements. These are bulk numbers calculated by aggregating verification over all grid points within large regions; they will not necessarily reflect skill for any sub-region.

For the operational forecasts of ESSO-IMD, the verification will be done for the forecast issued as per Table-3 given above.

7.4.1.3. Verification scores

After discussing many verification scores, the committee recommends the following minimum verification scores for verification of extended range and seasonal forecasts. These scores pertain to both deterministic and probabilistic forecasts.

1) Anomaly correlation coefficient (ACC) (for deterministic forecasts).
2) Mean Square Skill Score (MSSS) (for deterministic forecasts)
3) Relative Operating Characteristics (ROC) (both for deterministic and probabilistic forecasts)
4) Reliability diagrams (probabilistic forecasts)
5) Heidke Skill Score (HSS) (Categorical forecasts)

Anomaly correlation coefficient may be used only as a preliminary verification. More rigorous verifications may be done with other 4 scores mentioned above. MSSS is applicable to deterministic forecasts only, while ROC is applicable to both deterministic and probabilistic forecasts. MSSS is applicable to non-categorical forecasts (forecasts of continuous variables), while ROC is applicable to categorical forecasts either deterministic or probabilistic in nature. The verification methodology using ROC is derived from signal detection theory. This methodology is intended to provide information on the characteristics of systems upon which management decisions can be taken. In the case of weather/climate forecasts, the decision might relate to the most appropriate manner in which to use a forecast system for a given purpose. ROC is applicable to both deterministic and probabilistic categorical forecasts and is useful in contrasting characteristics of deterministic and probabilistic systems.

7.4.2 Verification methods for Short and Medium Range Prediction

7.4.2.1 Rainfall

In order to examine the performance of the model in the regional spatial scale for different homogeneous regions of the country, we selected six representative region (square/rectangular domain) for (a) All India land areas: (Lon: 68 ^{o} E – 98 ^{o} E, Lat: 9 ^{o} N – 37 ^{o} N), (b) Central India (CE: Lon: 75 ^{o} E – 80 ^{o} E, Lat: 19 ^{o} N – 24 ^{o} N), covering Vidarbha and neighborhoods, (c) East India (EI: Lon: 75 ^{o} E – 80 ^{o} E, Lat: 19 ^{o} N– 24 ^{o} N), covering Orissa and neighborhoods, (d) North-east India (NE: Lon: 90 ^{o} E – 95 ^{o} E, Lat: 24 ^{o} N -29 ^{o} N), (e) North-west India (NW: Lon: 75 ^{o} E – 80 ^{o} E, Lat: 25 ^{o} N -30 ^{o} N), covering Rajasthan and Haryana, (f) South Peninsular India (SP: Lon: 76 ^{o} E - 81 ^{o} E, Lat: 12 ^{o} N- 17 ^{o} N), covering Kerala and neighborhood and (g) West coast of India (WC: Lon: 70 ^{o} E - 75 ^{o} E, Lat: 13 ^{o} N - 18 ^{o} N), covering Konkan-Goa. The domains mean values of weekly (0-168h) cumulative rainfall forecast from both GFS T382 and T574 is compared against observation and, also the temporal and spatial correlation is computed.

In addition to these simple measures, a number of categorical statistics are applied. The term categorical refers to the yes/no nature of the forecast verification at each grid point. Some threshold (i.e., 0.1, 1, 2, 5, 10, 15, 35, 65 mm/day) is considered to define the transition between rain versus no-rain event. Then at each grid point (at the resolution of 50 km), each verification time is scored as falling under one of the four categories of correct no-rain forecasts (Z), false alarms (F), misses (M), or hits (H) as shown in Table-5. A number of categorical statistical skill measures are used, computed from the elements of this rain/no-rain contingency Table. They include

Bias score (Bias):

$$BS = \frac{F+H}{M+H}$$

Equitable threat score (ETS)

$$ETS = \frac{H-H_{random}}{H+M+F-H_{random}} \quad \text{where} \quad H_{random} = \frac{(H+M)(H+F)}{total}$$

7.4.2.2 Monsoon circulation features

In order to understand the characteristic features of monsoon rainfall captured by the model, performance of the model is also examined in terms of lower tropospheric circulation, vertically integrated moisture flux and precipitable water content. A case study of a monsoon depression is illustrated to examine the performance of the model during the episode of monsoon depression.

The precipitable water content (PWC) in an atmospheric column is given by:

$$PWC = \frac{1}{g}\int_{P_{sur}}^{P_{top}} q\,dp$$

where the limit of the integration is from the surface to the top of the atmosphere up to which the value of specific humidity q is non-zero and g is the acceleration due to gravity.

The vertically integrated water moisture flux is given by

$$Q = \frac{1}{g}\int_{sfc}^{top} qV\,dp$$

where **q** is specific humidity, **V** is the vector wind velocity, **p** is pressure, and **g** is gravity

7.4.2. 3 Upper air parameters

The verification statistics for GFS T382 and GFS T574 forecasts of upper air variables like wind, temperature and geo-potential height are computed over the regions referred to are: G2: Globe NHX: 20 ° N-80 ° N SHX: 20 ° S-80 ° S TRO: 20 ° S-20 ° N RSMC: 20 ° S-45 ° N: 30 ° E-120 ° E. Verification of upper air parameters is done at the 2.5°x2.5 ° grid resolution of Pattern correlation of model parameter is computed using anomalies respective to 30-year (1959-1988) climatology of the NCEP/NCAR reanalysis. The Root-Mean-Square Error for component wind is computed as follows,

$$V_f = u_f i + v_f j \;;\; V_o = u_o i + v_o j$$

where **f** stands for forecast and **o** observation/analysis

RMSE for u –component wind =sqrt {sum [$(u_f - u_o)*(u_f - u_o)$]} and
v –component wind =sqrt {sum [$(v_f - v_o)*(v_f - v_o)$]}

Chapter 8: Model performance and verification of models

8.1 Model performance and verification of high resolution GFS model & MME (IMD)

8.1.1 Observed and forecast fields

We begin with a description of observed fields of rainfall for the season (1 June to 30 September 2011). Fig. 17 (top panel, extreme left) illustrates the spatial distribution of mean rainfall of the season based on the observations. The observed rainfall distribution shows a north south oriented belt of heavy rainfall along the west coast with a peak of ~ 15 mm/day. The sharp gradient of rainfall between the west coast heavy rainfall and the rain shadow region to the east, which is normally expected, is noticed in the observed field. Another heavy rainfall belt (~ 20 mm/day) is observed over the North Bay of Bengal, extending from Myanmar coast to Orissa coast. A rainfall belt of order 10 -15 mm/day is noticed over the eastern central parts of the country over the domain of monsoon trough. Rainfall of the order to 10 to 15 mm/day is also observed over north-east India. Rainfall has been less than 5 mm/day over most parts of south peninsular India and extreme north-west India.

In general, the forecast fields (day-1,day-3 and day-5) of seasonal mean rainfall from GFS T382 (Fig.17 top panel : second to fourth) and GFS T574 (Fig.17 bottom panel) could reproduce the heavy rainfall belts along the west coast, over the north Bay of Bengal extending up to Myanmar areas. However, some spatial variations in magnitude are noticed.

In the forecast by GFS T382, 15 to 20 mm/day rainfall is noticed along the west coast in the day-1, day- 3 and day-5 forecasts, and an increasing trend with the forecast lead time. 15 to 20 mm/day rainfall belt lay over North Bay of Bengal, and the amount becomes 20 to 25 mm/day over Myanmar coast and adjoining areas. Over the north-east India and along the foot hills of the Himalaya, rainfall has been of the order of 15 to 20 mm/day. Rainfall has been of the order of 10 to 15 mm/day over the central India. Over the most parts of south peninsular India rainfall has been less than 5 mm/day.

In the forecast by GFS T574, 15 to 20 mm/day rainfall is noticed along the west coast in the day- 1, day-3 and day- 5 forecasts. A belt of 20 to 25 mm/day rainfall lay over north-east India and over the Myanmar coast. Rainfall has been of the order of 10 to 15 mm/day over central India – neighbouring regions and a decreasing trend with forecast lead time. Rainfall amount has been less than 5 mm/day over most parts of south peninsular India.

8.1.2 Spatial characteristics of forecast skills

In Fig.18, the spatial distribution of seasonal mean errors (forecast-observed) of rainfall (mm/day) at the resolution of 50 km based on day-1, day3 and day-5 forecasts of GFS T382 (top panel) and GFS T574 (bottom panel) for the period from 1 June to 30 September 2011 are demonstrated. Results of both GFS T382 and T574 show mean errors of the order of - 5 to + 5 mm/day for day-1, day 3 and day-5 forecasts over the country, except over the north-east India. Mean errors have been of the order of 15 to 20 mm/day over north-east India and over Myanmar coast and adjoining areas of north Bay of Bengal.

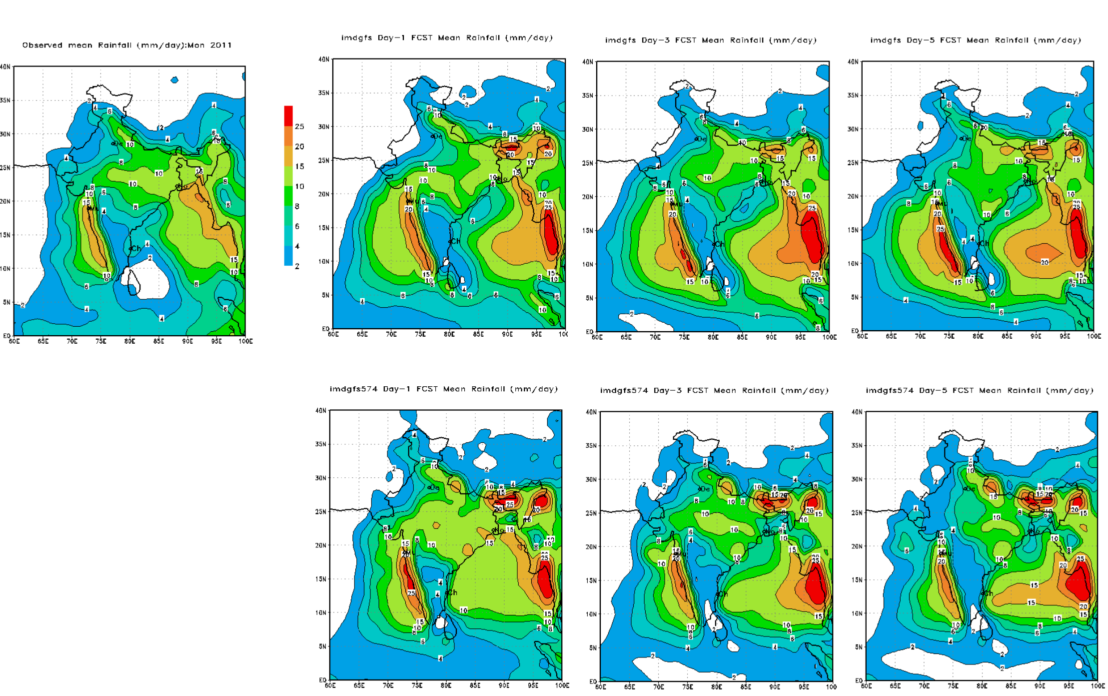


Fig. 17: Spatial distribution of seasonal mean observed rainfall (mm/day); and day-1, day-3 and day-5 forecast from *GFS T382* (top panel) and *GFS T574* (bottom panel) for the period from 1 June to 30 September 2011

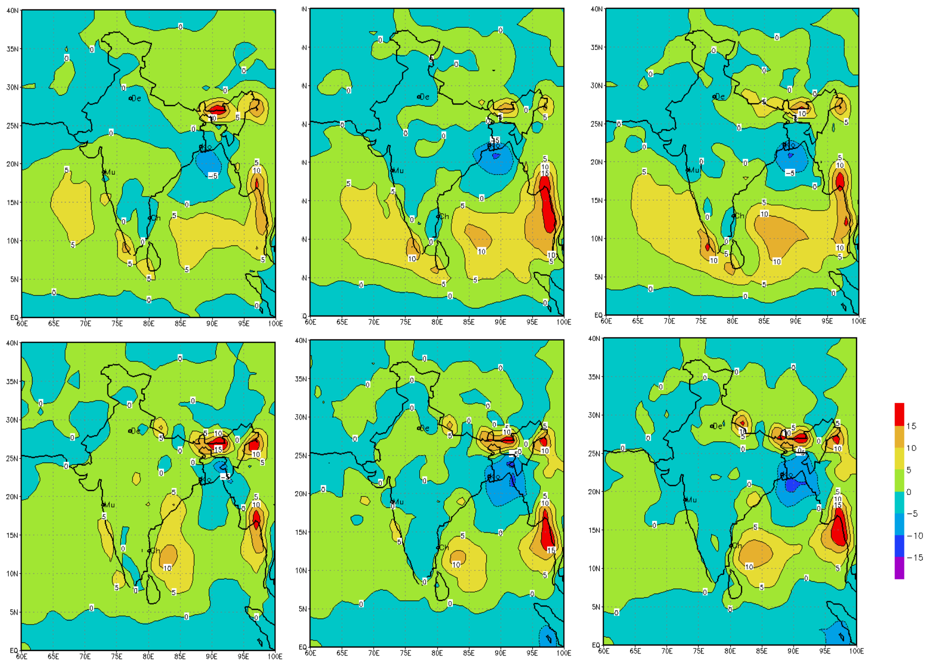


Fig. 18: Spatial distribution of seasonal mean error (forecast-observed) rainfall (mm/day) based on Day-1 to Day-5 forecast of *GFS T382* (top panel) and *GFS T574* (bottom panel) for the period from 1 June to 30 September 2011

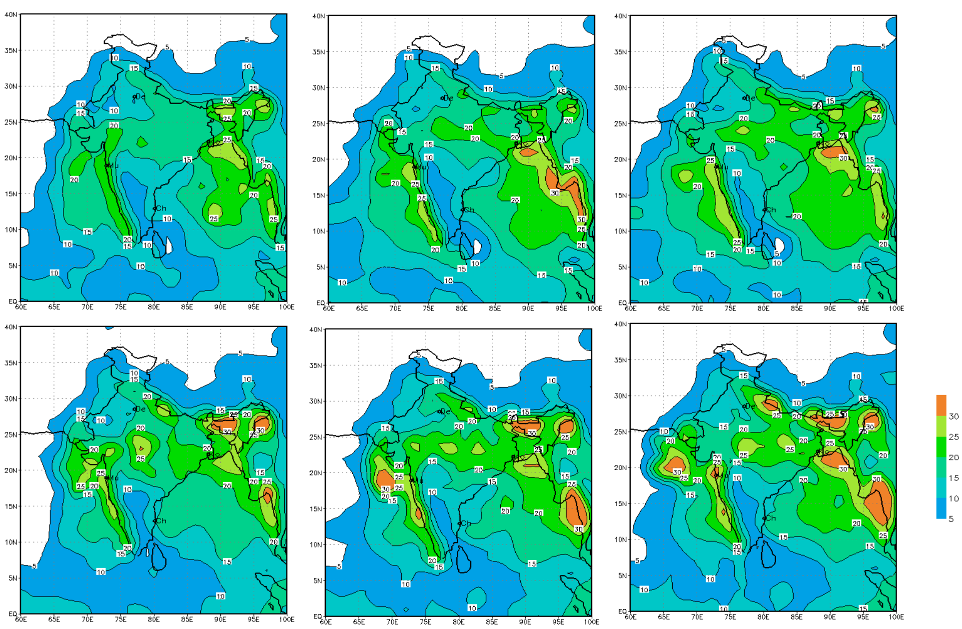


Fig. 19: Spatial distribution of seasonal root mean square error (rmse) rainfall (mm/day) based on day-1, day-3 and day-5 forecast of *GFS T382* (top panel) and *GFS T574* (bottom panel) for the period from 1 June to 30 September 2011

GFS T382 shows negative mean errors (less than 5 mm) over central India and North West Bay, over the domain of monsoon trough. Area of negative mean errors expands over most parts of the country with the forecast lead time. Large positive mean errors of the order of 10 to 15 mm/day lay over the central and adjoining south Bay of Bengal and also over south east Arabian Sea and an increasing trend with forecast lead time.

GFS T 574 shows positive mean errors (less than 5 mm/day) over most parts of the country in the day-1 forecast, except over east central India and adjoining north-west Bay, over the domain of monsoon low. With the forecast lead time, area of negative mean errors spread over most parts of the country.

The spatial distribution of seasonal root mean square error (RMSE) of rainfall (mm/day) based on day-1, day 3 and day-5 forecast of GFS T382 (top panel) and GFS T574 (bottom panel) for the period from 1 June to 30 September 2011 is shown in Fig. 19. The RMSE of day-1, day -3 and day-5 forecasts of the model has a magnitude between 1 and 20 mm, except over the Myanmar coast where the magnitude of RMSE exceeds 30 mm/day. Higher magnitude of RMSE (15 to 20 mm/day) are noticed over the domain of climatologically higher monsoon rainfall belts such as, west coast of India, north east India, central India – along the domain of monsoon trough and north-west bay of Bengal, over the domain of monsoon low. Magnitude of RMSE is found to be slightly higher for GFS T574, indicating higher variability in the performance of the model.

8.1.3 Region wise performance skill

In Fig.20 an inter-comparison of CC between T574 and T382 for the seven days cumulative rainfall against the observed rainfall for different homogeneous regions (central India, northwest India, north-east India, east India, southern peninsula, west coast of India and country as a whole) is presented. Inter-comparison clearly reveals that GFS T574 has better skill as compare to GFS T384 in all the homogeneous regions. In the regional spatial scale GFS T574 shows CC of order 0.7 and above.

An inter-comparison of CC for day-1 to day-5 forecasts by IMD GFS T382 and T574 for the country is shown in Fig. 21. The values of CC decreases ranging from 0.85 at day -1 to 0.70 at day-5 forecast. The results show that the GFS T574 has higher skill than that of T382 at all forecast days, particularly at day-2, day-3 and day-4 forecasts.

The CC for day-1 to day-5 forecasts of different homogeneous regions of India are shown in Fig. 22. For the north-west India CC for T382 ranges from 0.60 at day-1 forecast to 0.55 at day-5 forecast. The CC has been 0.10 higher in the T574 for the forecast up to day 4 and becomes equal at day-5 forecast. For the West coast of India CC for T382 ranges from 0.50 at day-1 forecast to 0.40 at day-5 forecast. The CC has been 0.20 to 0.30 higher in the T574 at all forecasts of day-1 to day-5. In central India, both for T382 and T574, the CC ranges from 0.75 at day-1 to 0.4 at day-5. The CC for T574 was slightly higher at day-1 and day-2 forecasts. For the north east India CC remains around 0.40 at all forecast days for T382. In the T574 the CC has been 0.1 to 0.30 higher at all forecasts. For south peninsular India, CC remains around 0.40 for T382. It has been 0.3 to 0.1 higher in the T574 forecasts.

The results show that the GFS T574 has relatively higher skill (at the regional spatial scale) than T382 at all forecast days. This indicates that the trend in domain mean daily rainfall in the day-

1 to day-5 forecasts of the GFS T574 model has been in the better phase relationship with the observed trend over most parts of the country.

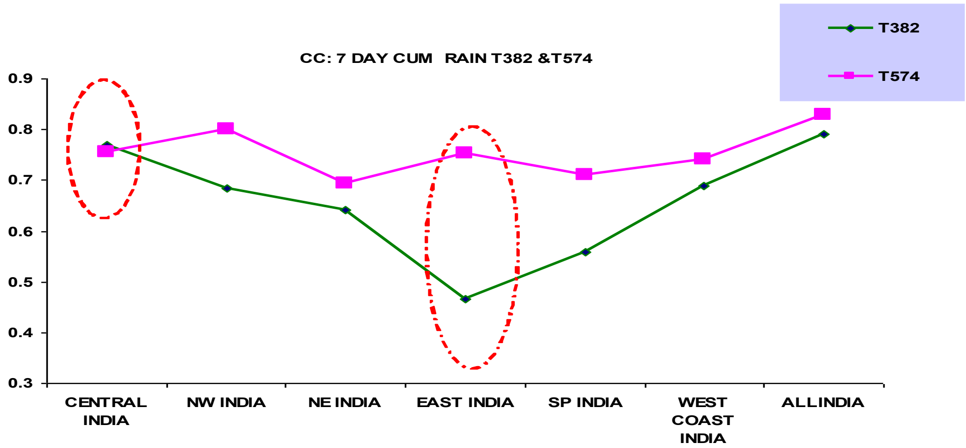


Fig. 20: Domain mean correlation coefficient (CC) of weekly (seven days) cumulative observed and corresponding seven days cumulative forecasts of rainfall by GFS T382 and T574 for different homogeneous regions of India during monsoon 2011

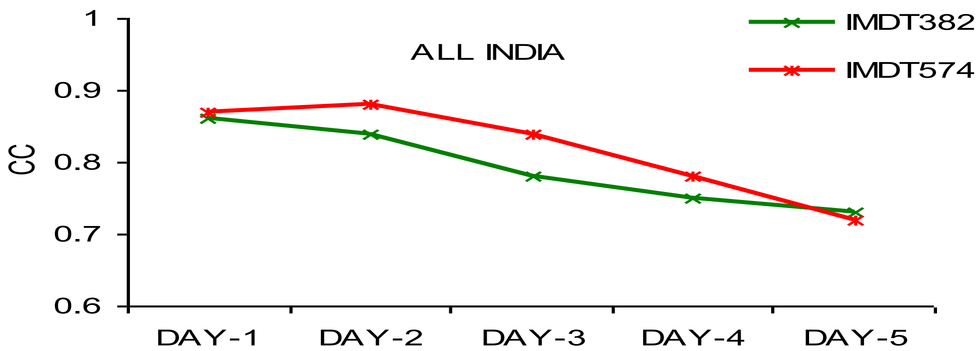


Fig. 21: Correlation coefficient of all India daily mean observed and corresponding forecast rainfall of day-1 to day-5 by GFS T382 and GFS T574 during monsoon 2011

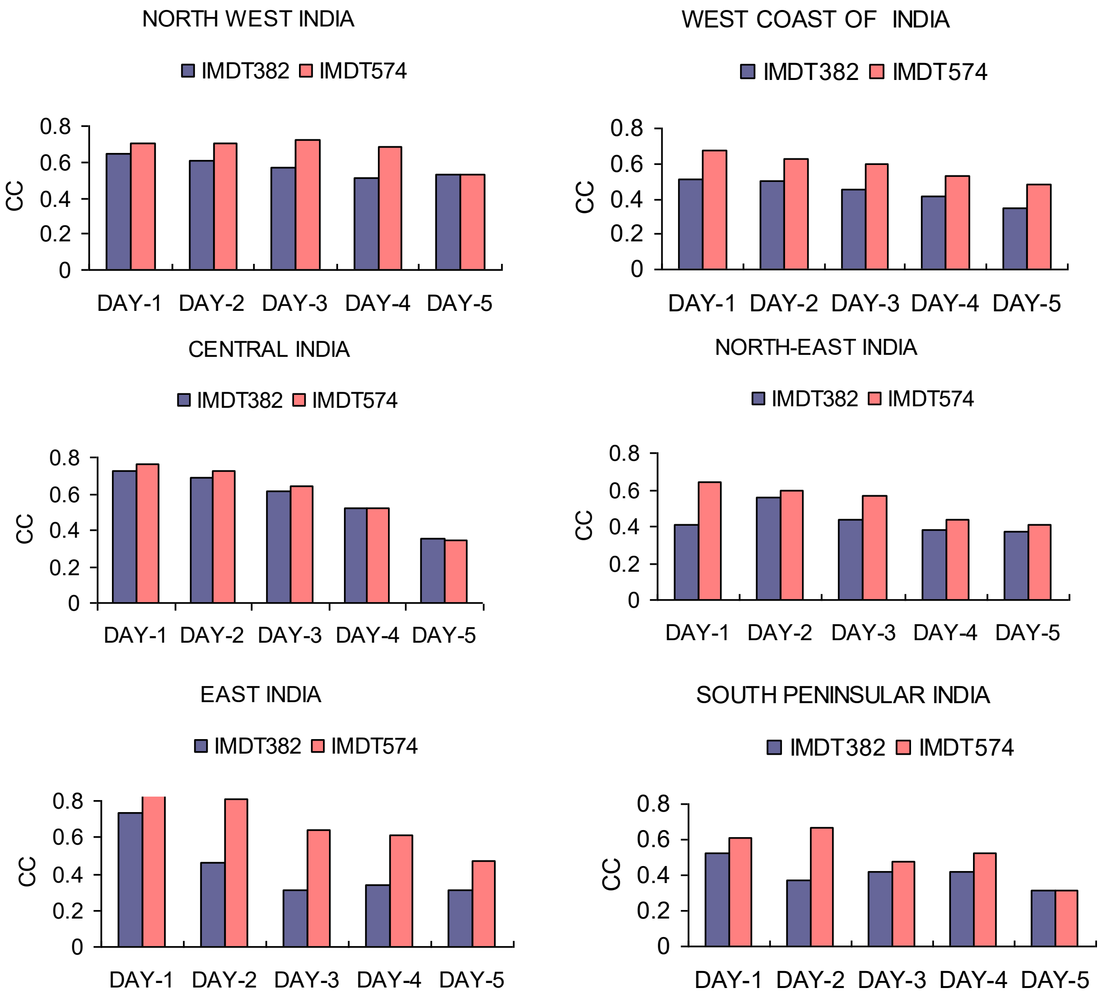


Fig. 22: Correlation coefficient of daily mean observed and day-1 to day-5 forecasted rainfall of GFS T382 and T574 over different homogeneous regions of India during monsoon 2011

8.1.4 Categorical statistical skill scores

The rainfall forecast skills are highly depended on the resolutions of verified grids/boxes (spatial) and time period (temporal). There is higher skill if the verified grids/boxes are very large or the time period is very long. The average of the forecast errors over a long period of time is a measure of the systematic part of the forecast error, while root-mean-square error (RMSE) is a measure of the random component of the forecast error. The correlation coefficient between trends in the forecast and observation is a measure of the phase relationship between them. The statistical parameters based on the frequency of occurrences in various classes are more suitable for determining the skill of a model in predicting precipitation. The aspect of model behaviour is further explored in Fig. 23 with bias score for classes with class marks of 0.1 mm , 1 mm, 2 mm, 5 mm, 10 mm, 15 mm, 35 mm, ...,65 mm. These skill scores are computed at the grid resolution of 50 km over the country.

The bias of a model forecast is the ratio of the predicted number of occurrences of an event to the number of occurrences of the same event actually realized in nature. It measures the ratio of the frequency of forecast events to the frequency of observed events. Indicates whether the forecast system has a tendency to under forecast (BIAS<1) or over forecast (BIAS>1) events. It does not measure how well the forecast corresponds to the observations, only measures relative frequencies. Fig. 23 shows the day-3 and day-5 bias of the GFS T382 and T574 model. Both the day-3 and day-5 bias of GFS T382 over predicts (bias >1) in the low threshold ranges up to 20 mm and under predicts (bias <1) rainfall event in the higher threshold ranges. While, the GFS T574 day-3 and day-5 bias over predicts (bias <1) rainfall event only up to 20 mm and above 20 mm the bias score is closer to 1.0.

ETS is used for the verification of rainfall in NWP models because its equitability allows scores to be compared more fairly across different regimes. If ETS = 1, it indicates that there is no error in the forecasting. ETS = 0 indicates that none of the grid points are correctly predicted. Fig. 24 shows ETS skill score of GFS T382 and GFS T574 for rainfall threshold of (a) 5 mm/day and (b) 15 mm/day for the homogeneous regions of India. ETS skill for rainfall threshold of 5 mm/day for GFS T574 is slightly higher than GFS T382 model in all the regions of study. ETS skill score is relatively high (order of 0.2 to 0.25) over west coast of India, where the rainfall variability is high. ETS skill is low over NE India for both the rainfall threshold of 5 mm/day and 15 mm/day. GFS T574 has slightly higher ETS skill than GFS T382 in all the regions. Interestingly, the day-1 to day-5 ETS score of GFS T574 remains relatively higher than GFS T382 in all thresholds and domains of study.

The error characteristics reflected in the results of categorical statistics is a common problem with any numerical models (Schultz 1995; Wang and Seaman 1997; Belair et al. 2000). At the high precipitation categories, the coarse-grid forecasts substantially under predict the rain amounts. This can be attributed to the coarse-grid global model resolution (0.23°), which does not permit the

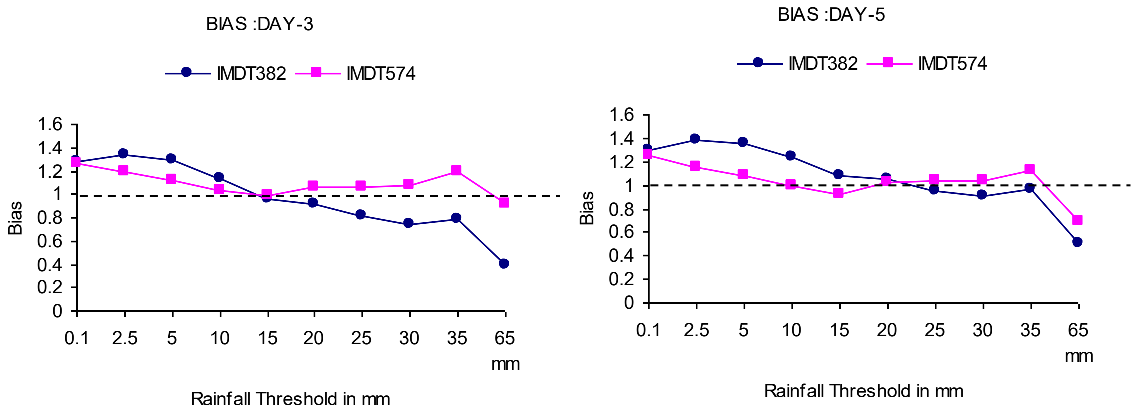


Fig. 23: Bias score for day-3 and day-5 forecast of GFS T382 and T574 over all India domain during monsoon 2011

correct representation of fine-scale convective motions that usually give the highest precipitation amounts.

8.1.5 Inter-comparison of rainfall forecast skill with other global models

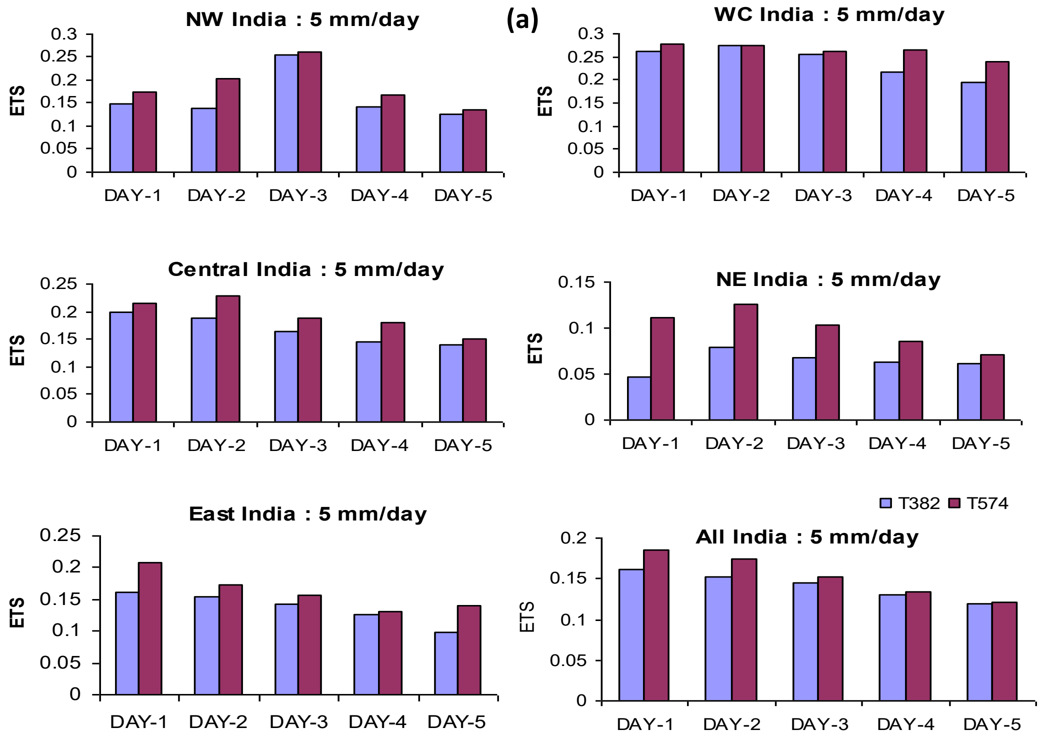
IMD implemented a Multi-model Ensemble (MME) five days rainfall forecast system (Roy Bhowmik and Durai, 2012), where five models from global leading NWP centres namely, IMD GFS, European Centre for Medium Range Weather Forecasting (ECMWF), Japan Meteorological Agency

(JMA), NCEP and United Kingdom Meteorological Office (UKMO) are used as the ensemble member. The weight ($W_{i,j,k}$) for each member model (k) at each grid (i,j) is obtained from the following equation:

$$W_{i,j,k}, = \frac{C_{i,j,k}}{\sum_{k=1}^{5} C_{i,j,k}}, \qquad i = 1, 2, \ldots, 161; \quad j=1,2,\ldots,161$$

$C_{i,j,k}$ = Correlation co-efficient between rainfall analysis and forecast rainfall for the grid (i,j) of model (k). For the computational consistency, $C_{i,j,k}$ is taken as 0.0001 in case $C_{i,j,k}$ is less than or equal to 0.

(a)



(b)

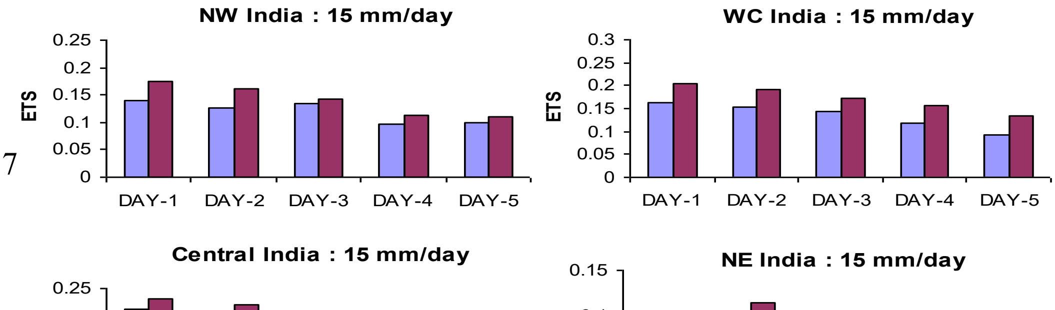


Fig. 24 : ETS Skill score of GFS T382 and T574 for rainfall threshold of (a) 5 mm/day and (b) 15 mm/day for the Homogeneous regions of India

Fig. 25 presents an inter-comparison of country mean spatial CC of rainfall forecasts by MME and individual models. The special CC is computed at the grid resolution of 50 km over the country based of daily forecasts during 1 June to 30 September 2011. The result shows that MME is superior to each member model at all the forecasts (day 1 to day 5), in which CC ranges from 0.52 at day-1 forecast to 0.38 at the day- 5 forecast. Among the member models UKMO is found to be superior followed by ECMWF, JMA, IMD GFS T574 (non-member), IMD GFS T382 and NCEP GFS T382. It is interesting to note that over the Indian region, IMD GFS (GFS operated at IMD) performed better compared to NCEP GFS (GFS operated at NCEP). This is because of positive impact of more local observations over India in the data assimilation system of IMD GFS.

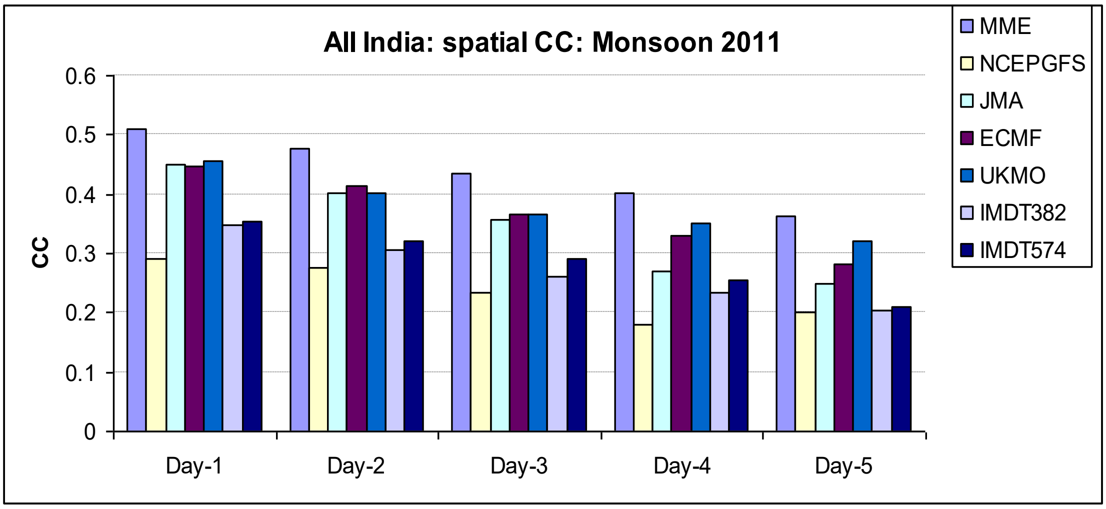


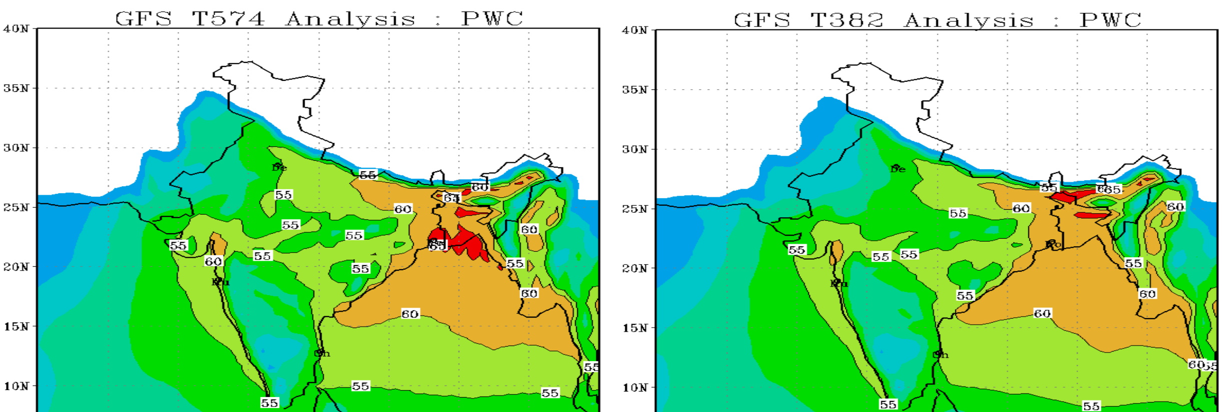
Fig. 25: An inter-comparison rainfall prediction skill based on mean spatial Correlation Co-efficient (CC) at the grid resolution of 50 km over the country on the basis of daily forecasts during 1 June to 30 September 2011.

8.1.6 Monsoon Circulation Features

In order to understand the characteristic features of monsoon captured by the model, in this section performance of the model is examined in terms of lower tropospheric circulation, vertically integrated specific humidity and precipitable water content.

Fig. 26 presents seasonal mean PWC (in mm) analysis and mean error of day-1, day-3 and day-5 forecasts from GFS T574 and GFS T382. PWC of higher magnitudes (60 mm to 65 mm) is located over the north Bay of Bengal and adjoining areas of east India and neighboring states. PWC of order 55 mm - 60 mm is found along foot hills, along the monsoon trough region, west coast of India and central Bay of Bengal. Similar pattern is noticed in the corresponding T382 analysis. In the T574, day- 1 forecast error (Fig. 26) shows negative error of order -2 to -3 mm along the region of south of the monsoon trough, some pockets over north west India, north-east India. A pocket of positive error is noticed over western part of the country and along the foot hills of Himalaya, The pattern remains same in the day- 3 and day- 5 forecasts, but with increasing magnitude of negative errors. The pattern of PWC mean error is found to be broadly matching with the corresponding mean error (under-estimation) pattern of rainfall over India.. A significant difference is noticed in the error pattern of PWC forecasts between GFS T574 and GFS T382. In the GFS T382, a belt of positive error is noticed over north east Arabian Sea and adjoin western parts of the country. A pocket of positive error is also noticed along the foot hills of Himalaya. A belt of negative errors are found across the country along 20 ^{o} N, over north east India and along northern parts of east coast. The pattern remains same in the day -3 and day- 5 forecasts with increasing magnitude of positive errors. The negative mean error of PWC over the central part and over east coast is in well agreement with the responding pattern of mean error of rainfall. But it is difficult to explain the reason for large positive mean error of PWC over the north east Arabian sea extending northward over the land.

In Fig. 27, zonally averaged (long 60 ^{o}E to 100 ^{o} E) specific humidity (g /kg) of analysis and day- 1 and day- 3 forecast errors from GFS T574 and GFS T382 for monsoon 2011 are presented. Both the analysis shows similar pattern with highest value of specific humidity (16 g /kg) below 950 hPa, which becomes 4 g /kg at around 600 hPa. There is a vertical extension of higher value of specific humidity between lat 20 ^{o} and 25 ^{o} N. GFS T574 forecast errors shows negative bias between 850 hPa and 650 hPa, extending northward up to 30 ^{o} N with two minima, one at the equator and another between 15 ^{o} -20 ^{o} N around 800 hPa. In the lower levels from surface between lat 10 ^{o} N and 15 ^{o} N, there is a negative bias of specific humidity. Above 550 hPa, the error is positive with a maximum value between 600 hPa and 500 hPa and lat 10 ^{o} N-15 ^{o} N. The magnitude of bias increases with the forecast lead time. GFS T382 shows negative bias below 850 hPa with a minimum value at 950 hPa between lat 5 ^{o} N-10 ^{o} N hPa and a strong positive bias above 850 hPa with a large domain of maximum value at 700 hPa between lat 5 ^{o} – 10 ^{o} N. A significant difference is noticed in the mean errors of these two forecasts. In Fig. 28, seasonal mean 850 hPa wind (m/sec) forecast errors of day- 1, day-3 and day-5 forecasts from GFS T574 and GFS T382 for monsoon 2011 are presented. GFS T574 forecast shows bias of westerly wind over most parts of the parts of country extending up to the foot hills (indicating weak monsoon trough) south-westerly bias over the north west India and northeast Arabian sea, and northerly bias over east coast of India and adjuring Bay of Bengal extending southwards up to 15 ^{o} N. Over the Myanmar it has been westerly bias. The magnitude of bias is found to grow with the forecast lead time. GFS T382 shows strong south-westerly bias over northwest India and adjoining Pakistan. In this case also considerable difference is noticed between the forecast errors of GFS T574 and GFS T382.



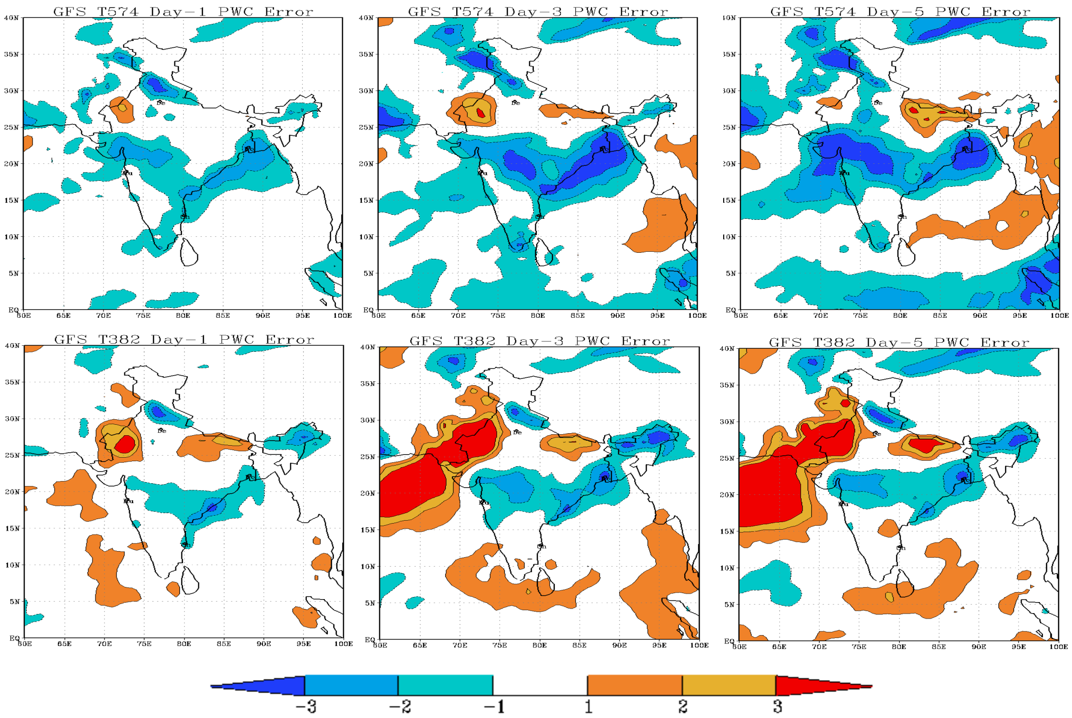
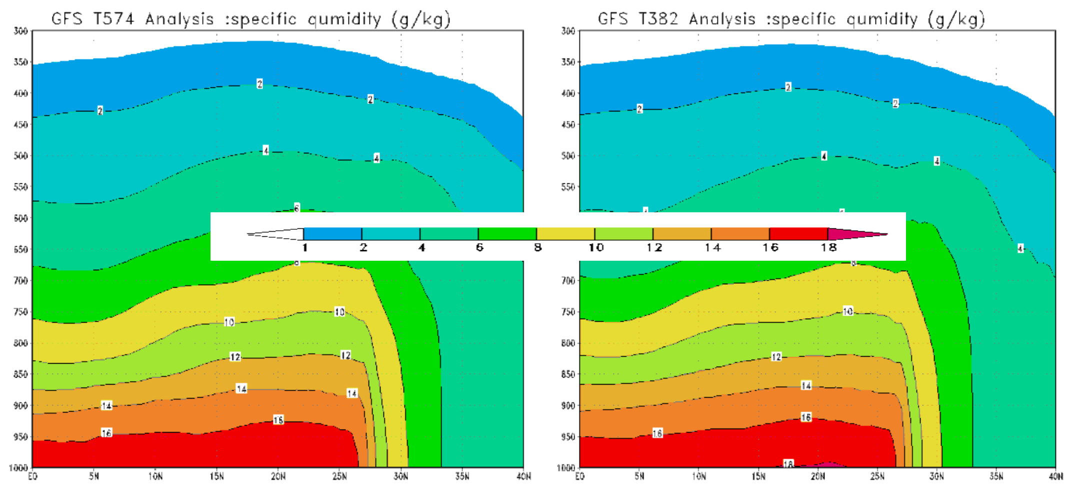


Fig. 26 : Seasonal (JJAS) mean precipitable water content (PWC in mm*)* analysis (top panel) and mean error of day- 1, day-3 and day- 5 forecasts from GFS T574 (middle panel) and GFS T382 (bottom panel) for monsoon 2011



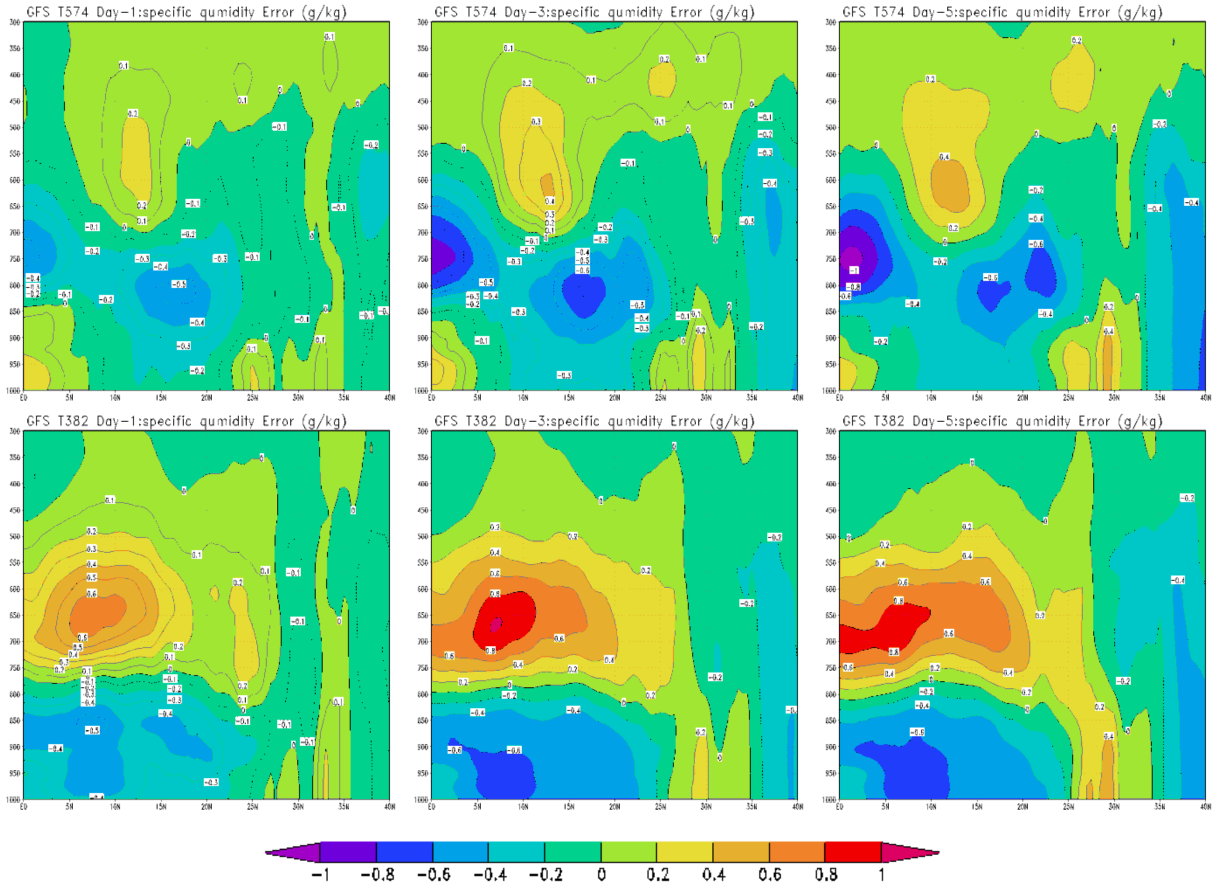
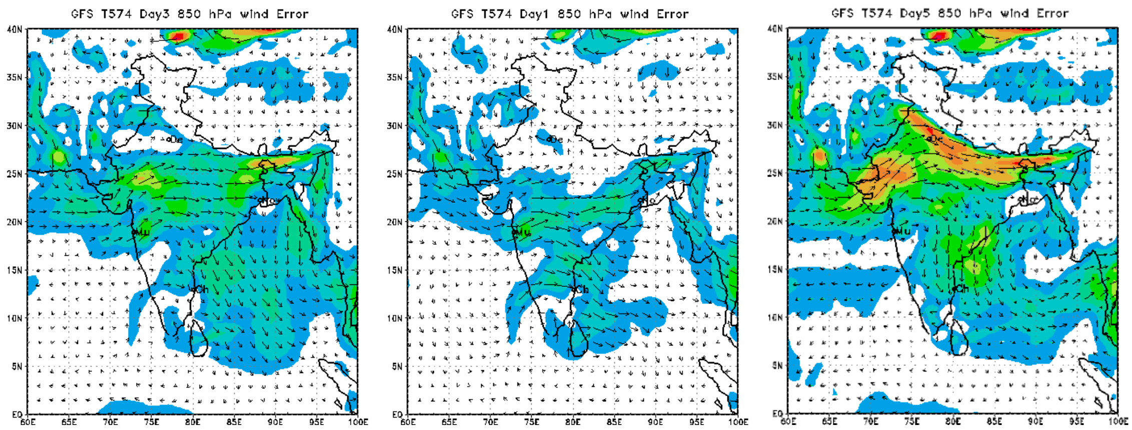


Fig. 27: Zonally averaged (Long: 60°-100E°) specific humidity (***g /kg)*** analysis (top panel) and day-1 and day-3 forecast error from GFS T574 (middle panel) and GFS T382 (bottom panel) for monsoon 2011



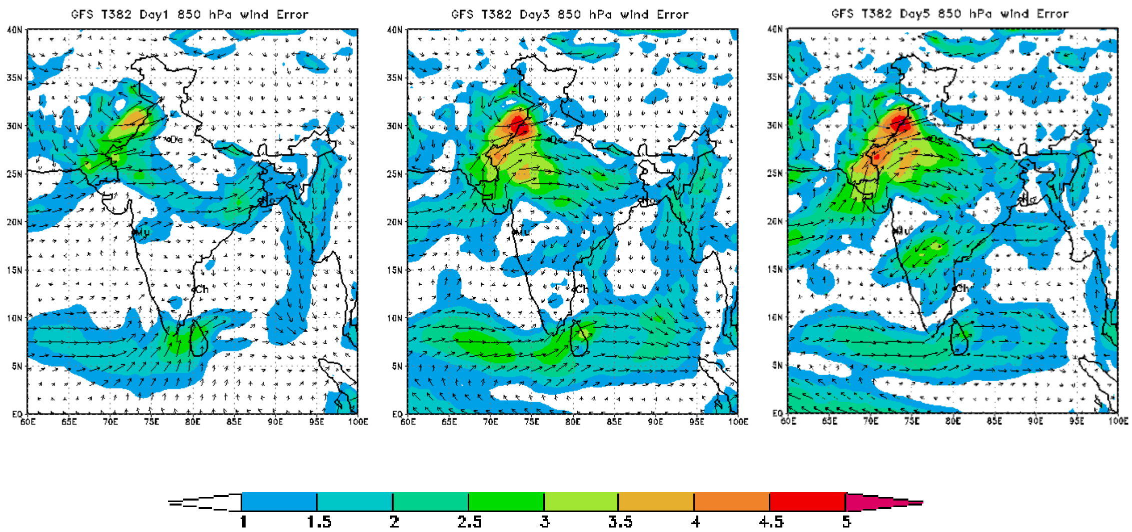


Fig. 28 : Seasonal (JJAS) mean **850** ***hPa*** wind error ***(m/sec)*** of day -1, day- 3 and day- 5 forecasts from GFS T574 (top panel) and GFS T382 (bottom panel) for monsoon 2011

8.1.7 Skill scores of Upper Air Parameters

The anomaly correlation of geo-potential height at 700 hPa, 500 hPa and 250 hPa over Globe, NHX, SHX, RSMC and Tropics for day-3, day-5 and day-7 forecast of GFS T382 and T574 are tabulated in Table 6a, 6b and 6c respectively. It is clearly seen that the GFS T574 has higher anomaly correlation compared to that of GFS T382, for almost over all the regions of study in all the three days (day-3, day-5 and day-7) of forecast. Tables 7(a, b, c**)** tabulates the anomaly correlation over Globe, NHX, SHX, RSMC and Tropics for temperature at 850, 500 and 250 hPa for day-3, day-5 and day-7 forecast of GFS T382 and GFS T574. The GFS T574 has higher anomaly correlation than that of GFS T382, for almost over all the regions of study in all the three days (day-3, day-5 and day-7) of forecast. In general the anomaly correlation (AC) of day-3, day-5 and day-7 forecast of T574L64 model is higher for geo-potential height and temperature in all the regions of study (Globe, NHX, SHX, RSMC and Tropics).

The mean values of GFS T382 and GFS T574 seasonal Root Mean Square Error (RMSE) of Zonal wind (m/sec) and Meridional wind (m/sec) based on day-1, day-3 and day-7 forecast for the period from 1 June to 30 September 2011 is shown in Table 8(a) –(c) and Table 9(a) –(c) respectively. Like anomaly correlation, the performance of T574 is better than the T382 in terms of root mean square error The RMS Errors in both the zonal and meridional wind of GFS T574 are lower as compared to T382 in all the regions i.e. Globe, NHX, SHX, RSMC and Tropics for all day-3, day-5 and day-7 forecasts. In all most all the regions and all the forecast hours, the RMSE of T574 is the lowest. With the advance in forecast days from day-3 to day-7, there is quantitative increase in the differences in RMSE between the forecasts of T574 and T382.

Table - 5: Rain contingency table applied at each grid point

	Predicted	
Observed	Rain	No Rain
Rain	H	M
No Rain	F	Z

Here, Z is the number of correct predictions of rain amount below the specified threshold, *F* is the number of false alarms, *M* is the number of misses, and *H* is the number of correct rain forecasts

Table 6a: Geo-potential Height Anomaly Correlation - Day-3 Forecast

	Global		NH		SH		RSM		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
700	0.94	0.943	0.942	0.947	0.941	0.945	0.845	0.874	0.788	0.822
500	0.943	0.947	0.946	0.953	0.942	0.947	0.853	0.876	0.807	0.846
250	0.947	0.952	0.944	0.955	0.948	0.953	0.904	0.918	0.803	0.856

Table 6b: Geo-potential Height Anomaly Correlation - Day-5 Forecast

	Global		NH		SH		RSM		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
700	0.81	0.829	0.808	0.822	0.809	0.831	0.701	0.775	0.66	0.728
500	0.815	0.834	0.815	0.831	0.812	0.833	0.712	0.761	0.681	0.754
250	0.824	0.843	0.813	0.838	0.823	0.841	0.808	0.846	0.697	0.757

Table 6c: Geo-potential Height Anomaly Correlation - Day-7 Forecast

	Global		NH		SH		RSM		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
700	0.62	0.653	0.608	0.623	0.623	0.662	0.571	0.672	0.569	0.645
500	0.627	0.66	0.618	0.636	0.624	0.665	0.565	0.639	0.605	0.674
250	0.638	0.669	0.624	0.651	0.631	0.671	0.666	0.732	0.611	0.672

Table 7a: Temperature Anomaly Correlation - Day-3 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	0.88	0.879	0.88	0.891	0.878	0.879	0.871	0.878	0.793	0.768
500	0.863	0.887	0.869	0.892	0.871	0.884	0.768	0.827	0.678	0.783
250	0.811	0.832	0.805	0.831	0.82	0.838	0.803	0.843	0.63	0.681

Table 7b: Temperature Anomaly Correlation - Day-5 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	0.747	0.76	0.738	0.767	0.735	0.748	0.791	0.812	0.691	0.696
500	0.703	0.742	0.706	0.747	0.704	0.726	0.648	0.732	0.526	0.676
250	0.636	0.669	0.631	0.666	0.632	0.664	0.721	0.768	0.486	0.574

Table 7c: Temperature Anomaly Correlation - Day-7 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	0.593	0.611	0.569	0.596	0.571	0.603	0.704	0.736	0.601	0.621
500	0.515	0.563	0.52	0.559	0.499	0.538	0.54	0.628	0.411	0.576
250	0.483	0.514	0.48	0.509	0.468	0.495	0.624	0.674	0.387	0.474

Table 8a: Zonal wind (U Comp) RMSE (m/sec) - Day-3 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	3.95	3.59	3.61	3.30	4.98	4.66	3.09	2.64	3.03	2.48
500	5.07	4.57	4.66	4.19	6.58	6.08	3.79	3.14	3.42	2.76
250	7.02	6.39	7.34	6.59	8.08	7.37	5.36	4.84	5.40	4.96

Table 8b: Zonal wind (U Comp) RMSE (m/sec) - Day-5 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	5.35	4.97	4.93	4.60	6.96	6.61	3.72	3.22	3.65	3.06
500	7.03	6.45	6.51	6.00	9.24	8.64	4.79	4.03	4.38	3.60
250	9.98	9.23	10.49	9.66	12.08	11.14	6.38	5.79	6.54	6.08

Table 8c: Zonal wind (U Comp) RMSE (m/sec) - Day-7 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	6.44	6.05	5.97	5.71	8.49	8.07	4.23	3.76	4.16	3.53
500	8.56	8.03	7.97	7.60	11.39	10.75	5.47	4.76	5.04	4.32
250	12.40	11.68	12.94	12.27	15.47	14.46	7.41	6.84	7.46	7.04

Table: 9a Meridional wind (V Comp) RMSE (m/sec) - Day-3 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	3.89	3.54	3.60	3.27	5.04	4.66	2.79	2.46	2.68	2.28
500	5.10	4.62	4.65	4.16	6.81	6.31	3.41	2.85	3.10	2.53
250	7.17	6.48	7.45	6.72	8.36	7.61	5.08	4.55	5.38	4.76

Table: 9b Meridional wind (V Comp) RMSE (m/sec) - Day-5 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	5.30	4.90	4.96	4.59	7.09	6.62	3.29	2.96	3.13	2.71
500	7.16	6.60	6.56	6.04	9.78	9.13	4.08	3.48	3.75	3.09
250	10.37	9.54	10.84	9.98	12.84	11.81	5.94	5.38	6.35	5.71

Table: 9c Meridional wind (V Comp) RMSE (m/sec) - Day-7 Forecast

	Global		NH		SH		RSMC		TRO	
Level	T382	T574	T382	T574	T382	T574	T382	T574	T382	T574
850	6.37	6.02	5.87	5.65	8.70	8.25	3.66	3.28	3.46	2.99
500	8.80	8.32	8.00	7.66	12.22	11.62	4.53	3.94	4.21	3.53
250	13.03	12.30	13.36	12.78	16.78	15.78	6.78	6.26	7.06	6.41

8.2 Performance of NCUM - the Unified Model of NCMRWF

8.2.1 Introduction for NCUM

Unified Model (NCUM) at a global horizontal resolution of ~25 km and 70 levels in the vertical and the associated 4D-VAR data assimilation system was successfully implemented at NCMRWF for real-time weather prediction in March 2012. Regional versions of NCUM at 12 km and 4 km horizontal resolutions & 70 vertical levels have also been implemented and tested for select seasons/cases. At NCMRWF GFS at a resolution of T574L64 and GEFS at a resolution of T190L28 are also being run in real-time.

8.2.2 Verification of Wind Forecasts against Observations

At NCMRWF, a set of diagnostics, which include forecast systematic errors and standard verification scores suggested by WMO/CBS are generated every month. During the recent years several changes have been implemented in the NCMRWF analysis-forecast system and the model performance over India has been evaluated. Verification of GFS and NCUM forecasts as per WMO/CBS suggestions is being carried on a monthly basis.

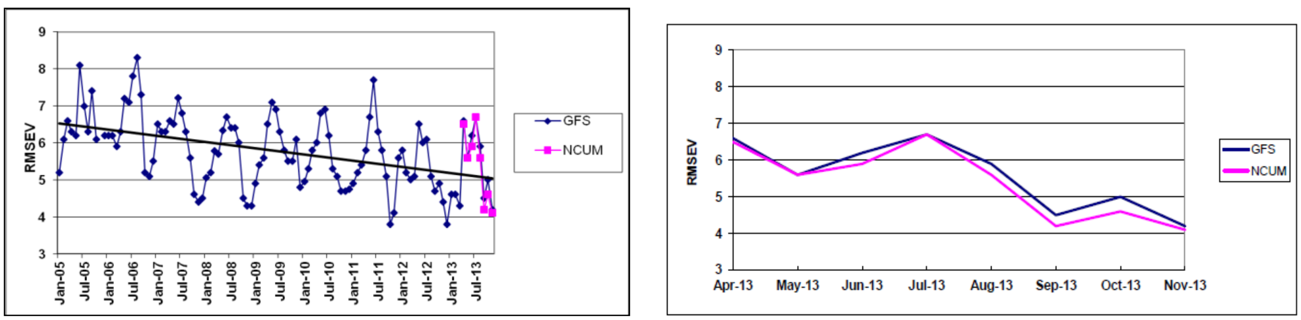


Fig. 29: RMSE of Day-3 forecast wind vector at 850 hPa

Fig. 29 shows the root mean square error (RMSE) of the magnitude of the wind vector (RMSEV) for the NCMRWF GFS model (blue line) Day-3 forecasts at 850 hPa level against the radiosonde observations over India since January 2005. The overall decrease in the RMSEV can be attributed to the increase in the resolution of the model, increase in the amount of data being assimilated and improvements in data assimilation techniques. The scores from NCUM forecasts (red line) show that the NCUM forecasts are marginally better compared to GFS.

8.2.3 Verification of Wind Forecasts against Respective Analyses

Fig. 30 shows the root mean square error (RMSE) of the magnitude of the wind vector (RMSEV) of the GFS (black line) , GEFS (red), NCUM (green) and UKMO (blue) against their respective analyses is conducted over Tropics (20^0S-20^0N) and RSMC-India and surrounding region (20^0S-45^0N, 30^0E-120^0E) for JJAS 2013. In the lower part of the figures the difference of the RMSEs from GEFS, NCUM and UKMO with respect to the RMSE from GFS is presented. The colour of the histograms corresponds to the same colour of the line depicting the forecast

RMSE and the RMSE differences. The RMSE differences outside the histograms are statistically significant at 95% level of significance. NCUM forecasts have been depicted till Day-5 and that of UKMO till Day-6. It can be seen from the figures that the NCUM forecasts have lower RMSEs as compared to GFS.

8.2.4 Categorical Verification of Rainfall Forecasts

The categorical verification scores are computed for each rainfall threshold based on all the observation/forecast pairs of each day during the monsoon season. The performance of the model forecasts (Day-5) are summarized using box and whisker plots in Figures 31 to 33.

The skill scores based on each day of the season are summarized using box and whisker plots. The left panels in the Fig. 30, 31 show the Probability of Detection (POD) and right panels show Success Ratio (SR). Both the scores indicate very good skill for rainfall thresholds below 20 mm/day. For 1 and 10 mm/day thresholds NCUM has higher POD (left panels) and marginally lower SR (right panels). Lower SR in NCUM than in GFS suggests NCUM forecasts have higher false alarms than in GFS forecasts for these rainfall thresholds. For 1 and 10 mm/day thresholds NCUM shows higher POD in Day-5 forecast along with higher SR in Day-5 forecasts. Similarly for 40 mm/day threshold the NCUM forecasts show lower POD and higher SR compared to GFS. This means for higher rainfall thresholds NCUM has lower hit rate and also lower false alarms. Both models show low POD and SR for higher rainfall thresholds (80 mm/day) indicating poor skill along with increasing number of outliers for higher rainfall thresholds.

The panels in the Fig. 32 show the Probability of False Detection (POFD) on left and Extreme Dependency Score (EDS) on right. The box and whisker plots showing the POFD indicate that NCUM forecasts have high false alarms compared to GFS forecasts. For all thresholds up to 20 mm/day the NCUM forecasts show higher EDS.Similarly the panels in the Fig. 33 show the box and whisker plots for two summary scores, the Equitable Threat Score (ETS) and Hanssen and Kuipers Score (HK Score). With rather low ETS values both models have moderate skill. NCUM does a better job in separating ‘yes’ events from ‘no’ events for 1, 10 and 20 mm/day thresholds.

8.2.5 Performance during severe weather

The performance of NCUM in the recent severe weather events (viz., heavy rainfall over Uttarakhand and Tropical Cyclone “Phailin” are briefly described below:

Uttarakhand Rainfall

Fig. 34 shows the forecast rainfall and wind at 600 hPa from NCUM valid for 00z 17 June 2013 along with the analysed IMD-NCMRWF rainfall and model analysis. It is clear from the figure that NCUM has predicted winds reasonably well till Day-5 and rainfall till Day-3.

Fig. 35 compares the correlation coefficient and probability of detection (POD) of rainfall from NCUM, GFS and UKMO. It is clear from the figure that NCUM performs better than GFS and UKMO on all days.

Tropical Cyclone Phailin

Fig. 36 compares the average forecast track errors (during 9-12 October 2013) for Tropical Cyclone Phailin from NCUM, GFS and GEFS. It is clear from the figure that NCUM has the lowest forecast track errors for this tropical cyclone.

8.2.6 Conclusions

The unified model (NCUM) operational at NCMRWF have been found to be performing consistently better than GFS in all model evaluations conducted during last few monsoon, winter and cyclone seasons. Further improvements can be expected with the implementation of a hybrid 4D-Var data assimilation based on a 44-member global ensemble prediction system at a resolution of 33kmL70 on the new HPC.

List of Acronyms

NCUM - Unified Model running daily at NCMRWF

GFS - Global Forecast System running daily at NCMRWF

GEFS - Global Ensemble Forecast System running daily at NCMRWF

UKMO – Unified Model running at Met Office, UK

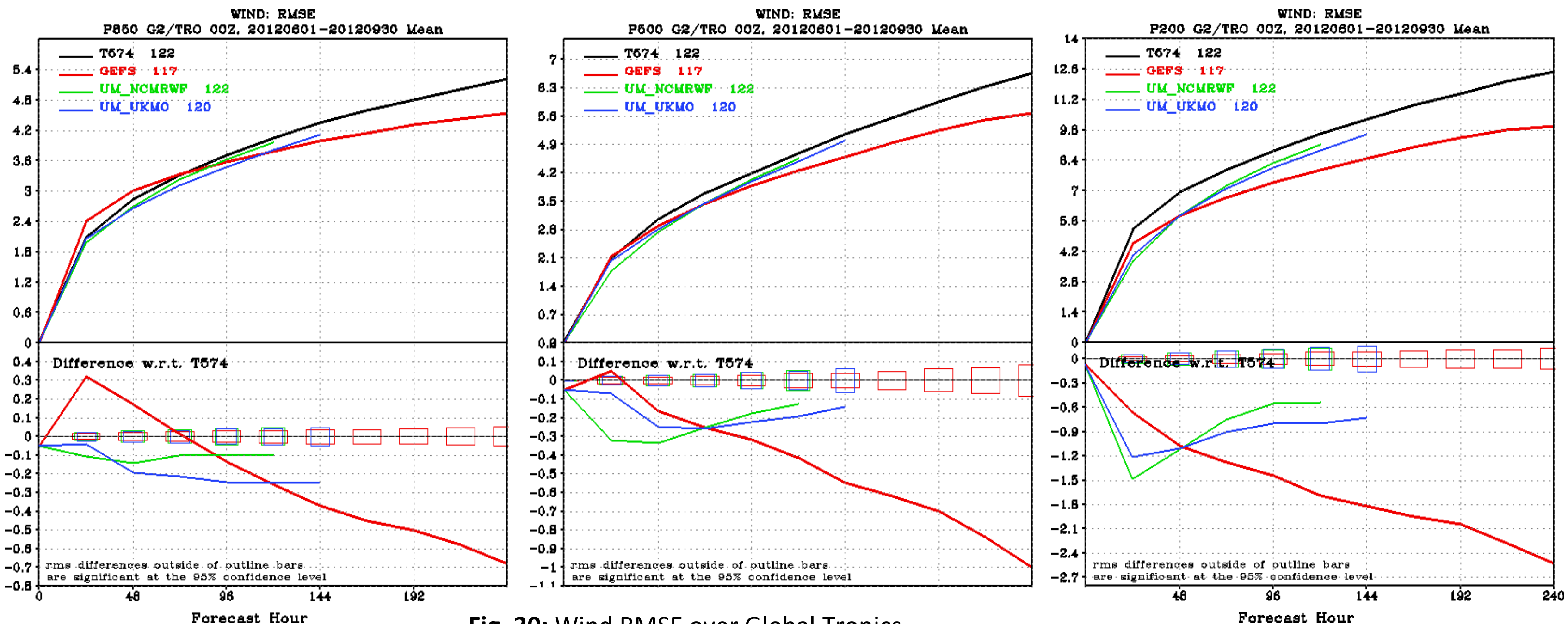


Fig. 30: Wind RMSE over Global Tropics.

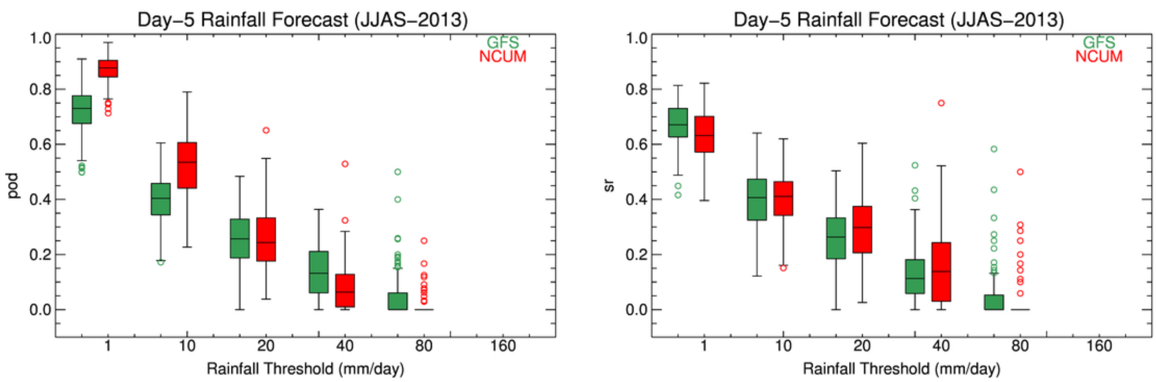


Fig. 31: Probability of detection (POD; left) and False Alarm Ratio (FAR; right) in Day-5 forecasts of GFS and NCUM for various rainfall thresholds.

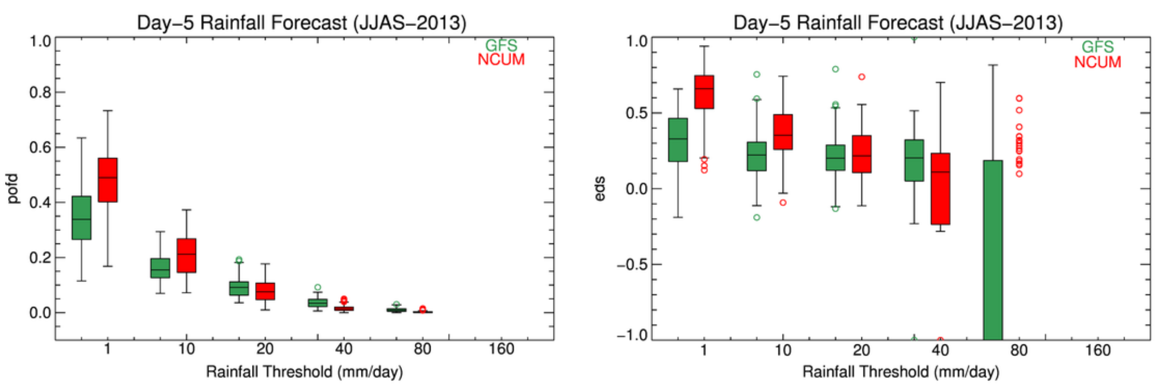


Fig. 32: Probability of false detection (POFD; left) and Extreme dependency score (EDS; right) in Day-5 forecasts of GFS and NCUM for various rainfall thresholds.

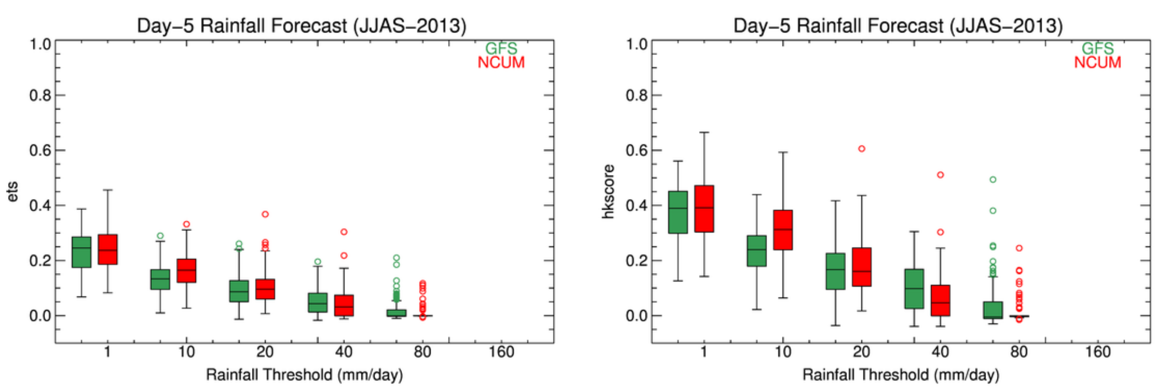


Fig. 33: Equitable Threat Score (ETS; left) and Hanssen and Kuipers Score (HK Score; right) in Day-5 forecasts of GFS and NCUM for various rainfall thresholds.

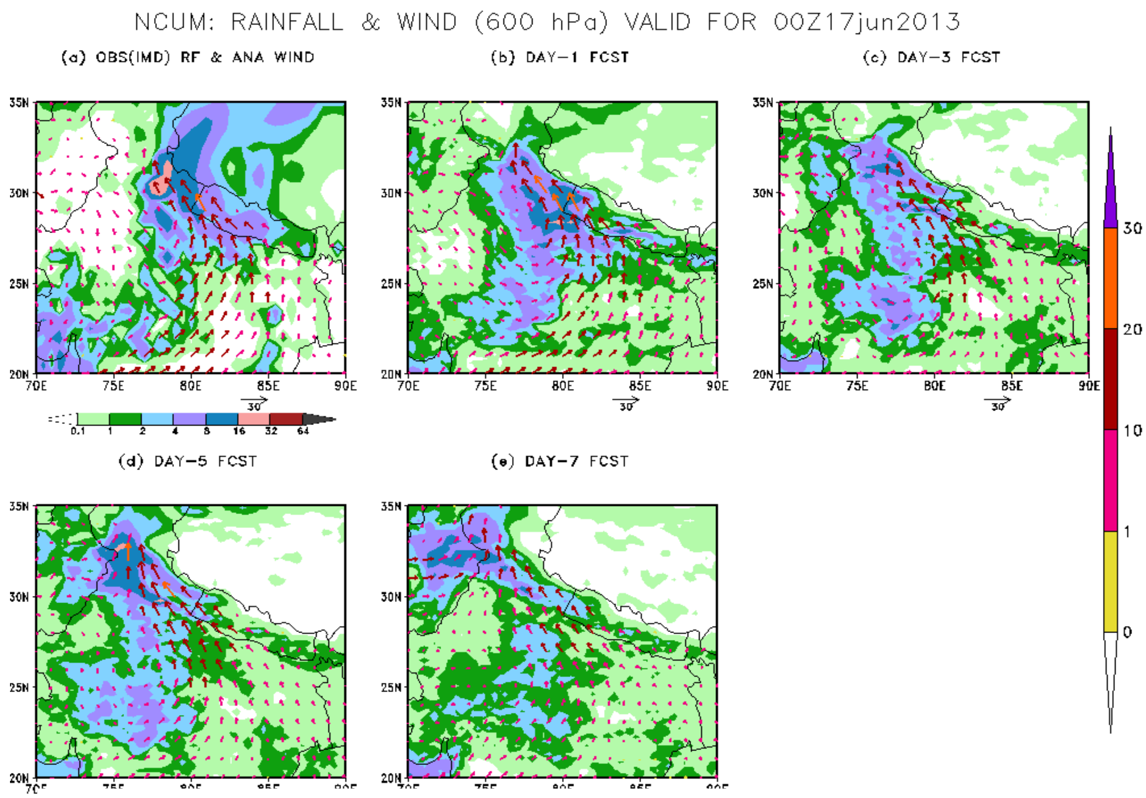


Fig. 34: Forecast rainfall & wind (600 hPa) from NCUM valid for 00 UTC 17 June 2013 along with analysed rainfall & wind

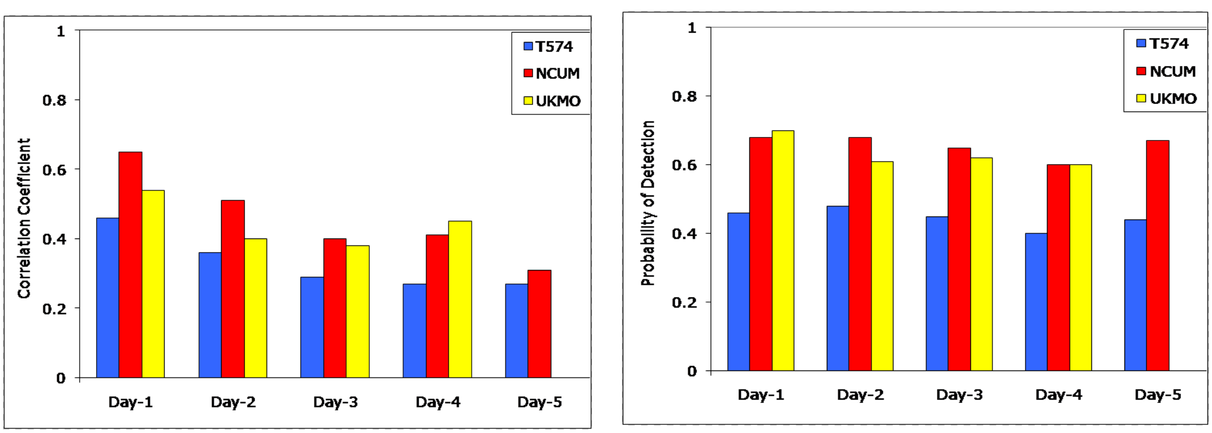


Fig. 35: Comparison of correlation coefficient and POD of rainfall (valid for 00 UTC 17 June 2013) from NCUM, GFS and UKMO

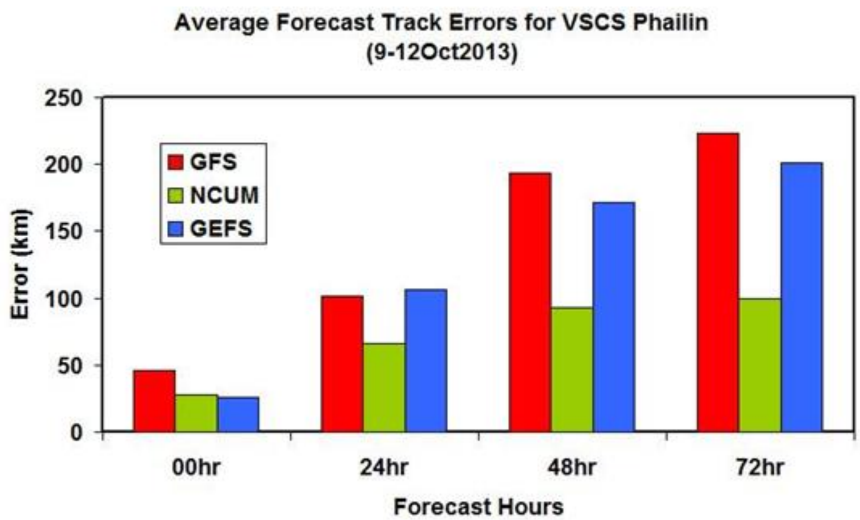


Fig. 36: Average forecast track errors for Tropical Cyclone Phailin from NCUM, GFS and GEFS during 9-12 October 2013

8.3 Summary of validation results

Performance of the model is examined in terms of rainfall, vertically integrated specific humidity, lower tropospheric wind circulation and precipitable water content (PWC) to understand the monsoon rainfall features captured by the model. The verification of rainfall is done in the spatial scale of 50 km, in a regional spatial scale and also country as a whole in terms of skill scores, such as mean error, root mean square error, correlation efficient, and categorical statistics such as, bias score and ETS. The result demonstrates that the performance of GFS T574 and GFS T382 in predicting rainfall varies with geographical location and synoptic regime. For both the model, mean errors have been of the order of 15 to 20 mm/day over north-east India and over Myanmar coast and adjoining areas of north Bay of Bengal. With the forecast lead time (from day -2 onward) , area of negative mean errors spread over most parts of the country. Magnitude of RMSE is found to be slightly higher for GFS T574, indicating higher variability in the performance of the model. Validation results shows that both the GFS T382 and T574 model forecasts, in general, are skillful over the regions of climatologically heavy rainfall domains. However, the accuracy in prediction of location and magnitude of rainfall fluctuates considerably. Both the model forecasts have reasonably good capability to capture large scale rainfall features of summer monsoon, such as heavy rainfall belt along the west coast, over the domain of monsoon trough and along the foot hills of the Himalayas. In general, both the model showed considerable skill in predicting the daily and weekly accumulated rainfall amounts when averaged over the country. However the quantitative inter-ccomparisons of these results have clearly demonstrated the superiority of GFS T574 against the GFS T382.

No appreciable difference is noticed between the analysis fields of GFS T574 and GFS T382 in terms of vertically integrated specific humidity, PWC, zonally averaged specific humidity and lower tropospheric wind pattern. But in the corresponding forecast errors considerable differences between GFS T574 and T382 are noticed. The magnitude of error for these parameters increases with forecast lead time in both GFS T574 and T382. In the GFS T382, a belt of large positive error of PWC is noticed over north east Arabian Sea and adjoining western parts of the country, which is unlike GFS T574. Otherwise, the mean errors of PWC over most parts of the country are negative in both GFS T574 and T382, which is found to be broadly in well agreement with the corresponding mean error (under-estimation) pattern of rainfall over the country. Zonally averaged specific humidity shows that in the lower troposphere below 550 hPa between lat 10 º N and 15 º N, there is a negative bias of specific humidity. Above 550 hPa, the error is positive with a maximum value between 600 hPa and 500 hPa and lat 10 º N-15 º N.. GFS T382 shows negative bias below 850 hPa with a minimum value at 950 hPa between lat 5 º N-10 º N hPa and a strong positive bias above 850 hPa with a large domain of maximum value at 700 hPa between lat 5 º – 10 º N. GFS T574 forecast shows bias of westerly wind over most part of central and north India extending up to foot hills of Himalaya, south-westerly bias over the north west India and northeast Arabian sea, and northerly bias over east coast of India and adjuring Bay of Bengal extending southwards up to 15 º N at 850 hPa. GFS T382 shows strong south-westerly bias over northwest India and adjoining Pakistan, where precipitable water contents showed strong positive bias.

Chapter 9: Observational studies and requirements

A number of observational campaigns such as CTCZ (Continental Tropical Convergence Zone), CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement), STORM (Severe Thunderstorms Observation, Research and Modeling), involving a large number of operational, research and academic groups are under way. The observational data collected in these programmes are likely to help process studies and improve the way physical processes are included in numerical models. A number of field campaigns for improving monsoon prediction have been organized (MONTBLEX, LASPEX, BOBMEX, ARMEX etc.)

It is expected to support some observational campaigns with a major focus on improving model parameterization schemes, both in Atmosphere and Oceans. Similarly the observation in Bay of Bengal are very limited and the mixing processes under freshwater lens are not well understood, therefore a program on measuring and understanding mixing processes in the Bay of Bengal is highly essential for parameterizing mixing in the Ocean models. To investigate the above, a multi-institutional national observational program has been proposed to Monsoon Mission, by Prof. Debashis Sengupta (of IISc, Bangalore as PI of the proposal) and Co-PIs from INCOIS, Hyderabad; IISc, Bangalore; NIOT Chennai; SAC, Ahmedabad and NIO Regional Centre of Visakhapatnam and the proposal has been approved by MoES. Their aim is to obtain multi-scale observations in the near-surface Bay of Bengal, a reference surface flux dataset, and observations in the atmospheric boundary layer across seasons. Synthesis of observations and process models will be used to guide efforts to improve (i) estimates of basin-scale surface fluxes, and (ii) parameterisation of upper ocean processes in ocean models, towards more realistic simulation of basin-scale SST. A major goal is to build basic infrastructure and capacity in fine-scale observations and modeling through international collaboration and training.

For atmospheric observations and observational studies related to physics and dynamics of the tropical Clouds, IITM is conducting CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement) and several other field campaigns over the country.

9.1 Ocean Studies: Coupled Physical Processes in the Bay of Bengal and Monsoon Air-Sea Interaction (IISC / INCOIS)

9.1.1 Motivation

The hydrological cycle in the ocean and atmosphere are intimately linked over the river-dominated Bay of Bengal. The warm, moist monsoon atmosphere supports convection on many space-time scales. A thin surface layer of river and rain water in the central and north Bay is very sensitive to surface forcing. Sea surface temperature (SST) responds to heat flux with large-amplitude oscillations, and changes in SST feed back to the atmosphere. However, we lack knowledge of key physical processes responsible for the unique air-sea interaction in this basin.

The main target of atmospheric prediction is monsoon rainfall in the south Asian region, but rainfall is coupled to the changing patterns of Bay of Bengal SST on synoptic to intra-seasonal time scales. Improved prediction of the coupled system demands knowledge of small -scale physical processes that determine SST, surface fluxes, and the structure of the upper ocean and atmospheric boundary layer.

9.1.2 Objectives

The main objective of ocean observations is **to understand physical processes in the near-surface ocean and atmosphere, and their role in basin-scale air-sea interaction.** Results from the IOP will be used to guide efforts to improve (i) surface fluxes and (ii) parameterisation of upper ocean processes in ocean models, towards more realistic simulation of basin-scale SST.

9.1.3 Science Issues and Questions

The overarching theme is **coupled variability of the warm, fresh ocean boundary layer and the warm, moist atmospheric boundary layer**. The broad science issues and questions are organised in four sub-themes, to be addressed by observation-model synthesis. Science background and current status is presented in later sections.

Freshwater:

* The pathways of river and rain water; how does surface freshwater maintain its identity across seasons ?
* How does low-salinity water reach 50-100 m depth in the northern Bay ?
* Characteristic freshwater structures (river plumes, lenses, eddies, filaments, fronts).
* Near-surface currents forced by lateral salinity gradients.

Upper ocean mixing and SST:

* Key mixing processes (tides, surface forcing, frontal dynamics, sub-mesoscales) ?
* How does freshwater influence mixing; vertical distribution of momentum and heat (surface momentum trapping, barrier layers, temperature inversions) ?
* The role of freshwater in basin-scale SST evolution.

Surface fluxes and boundary layers:

* Optical properties of river water and SST; subsurface radiation and temperature.
* Why are sea-air gradients in the Bay so different from other warm oceans ?
* Algorithms for surface layer scales (u^*, q^*, θ^*) and air-sea fluxes.

Multi-scale air-sea interaction:

* Local air-sea interaction, atmospheric stability and rainfall.
* Synoptic to sub-seasonal coupling of upper ocean to ABL; is the coupling different in the north and south Bay?
* Are diurnal cycles in the ocean and atmosphere coupled; does the diurnal cycle rectify to longer scales ?

9.1.4 Approach

The main elements are: Continuous observations from moorings, drifters, autonomous floats; regular surveys using ships, towed instruments, and gliders; an IOP with small-scale process observations integrated with process models; analysis of IOP observations with other in situ data, satellite data, and models. In order to go from small -scale physical processes to basin-scale air-sea interaction, we need observations in different seasons and contrasting regimes (boundaries/open ocean, north/south Bay, convectively active/quiet periods). Multi-scale ocean models and regional coupled models will be used to interpret and provide context to the observations. The post-IOP phase will focus on parameterization in ocean general circulation models (GCM's) towards improvement of SST simulation. We need collaboration with international groups on observing techniques and models to study fine-scale processes (we do not have a strong research tradition in these areas). Training of Ph.D. students, younger scientists and technicians is an important part of the programme.

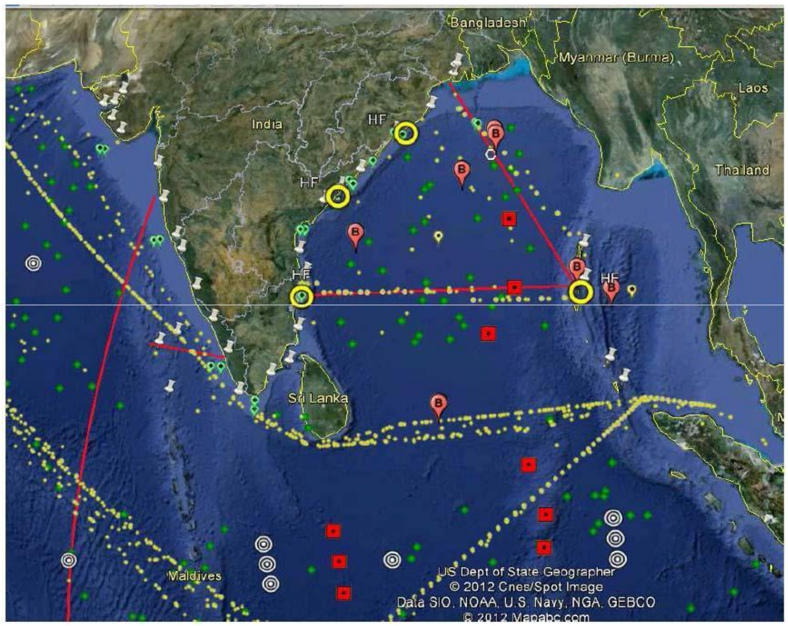


Fig. 37 : Present status of observing system. ARGO: green dots; XBT: red lines, yellow dots; Tide gauge: white pins; RAMA moorings: red squares; NIOT moorings: red balloons; Current meter moorings: concentric circles; Seabed ADCP: twin green balloons; CODAR/HF Radar: open yellow circles; and Upper ocean mooring: white hexagon.

A summary of the existing observing systems in the northeast Indian Ocean, and the proposed Bay of Bengal observations, is presented as two schematics below (**Fig. 37 and 38**); details of implementation will be worked out at a later stage.

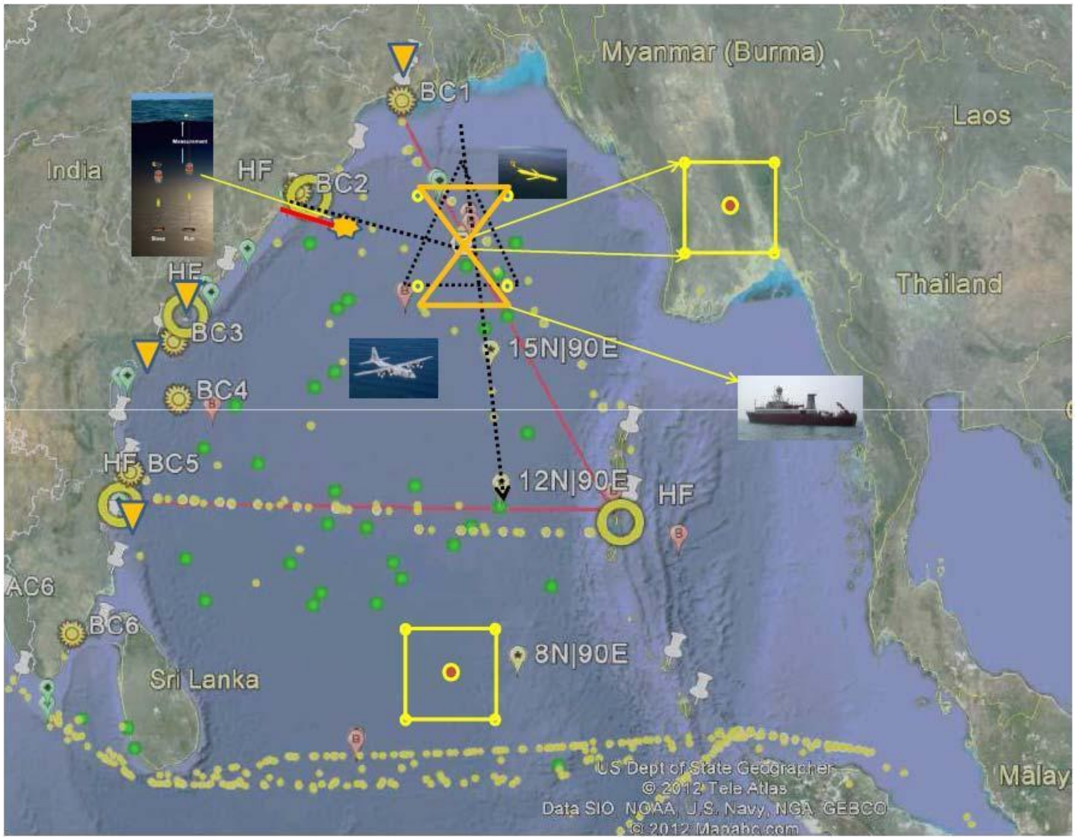


Fig. 38 : Proposed Bay of Bengal observations (bold) overlaid on existing observing system (faint). Surface wave buoy: yellow sun; Doppler weather radar: inverted triangle; Mooring polygon ("observatory") 8ºN & 18ºN: yellow square with red centre; Western boundary mooring array: red line; Glider and ship (notional) tracks: black dashed line, yellow line; Moored profiler: yellow star; Aircraft.

9.1.5 Science Background

9.1.5.1 Large-scale context

The Bay of Bengal is distinguished by a fresh, light near-surface layer that is very sensitive to surface forcing. The unique characteristics of the atmosphere and ocean, specially in the north Bay, permit air-sea interaction on short time scales (Bhat 2001, 2003). This brief introduction to the Bay of Bengal and the coupled air-sea-land system in the south Asian monsoon region is focused mainly on intra-seasonal oscillations of the summer monsoon. It is based on selected recent literature and unpublished material. For more context and references, see

Varkey (1996), Schott (2001), Shankar (2002), Gadgil (2003), Webster (2006), Waliser (2006), Schott (2009) and Goswami (2012).

Several major rivers flow into flow into the north Bay of Bengal, including the Ganges-Brahmaputra-Meghna (“Meghna”), the world's third largest river after the Amazon and Congo. Satellite altimetry and gauge data show that water level in the Meghna rises 7 m from winter to summer, when discharge is highest (Papa 2010, Jian 2009). The total catchment area of the major rivers is about 2 million km^2 , nearly equal to the area of the Bay. Annual river runoff (R; 3000 km^3) and rainfall (P; 4500 km^3) exceed annual evaporation (E; 3500 km^3) by 4000 km^3 (Sengupta, 2006**)**, about 1.6 m (errors 10-20%). Annual mean surface heat flux Q_{net} is 20-30 W/m^2 into the ocean.

The Bay of Bengal has to export heat and water (volume), and import salt. Models suggest a shallow cross-equatorial meridional overturning circulation in the north Indian ocean, with complex space-time structure (Miyama 2003). Upper ocean transport has been measured across selected sections in the Arabian Sea, the equatorial Indian ocean and south of Sri Lanka (Schott 2001), but long time series are not available from the lateral boundaries of the Bay of Bengal.

A shallow meridional circulation requires upper ocean mixing in the tropical Indian Ocean – candidate locations are summer upwelling regions off Africa and Arabia, southern India and Sri Lanka (Varadachari 1967), and occasionally Sumatra and in the

Seychelles thermocline ridge in all seasons (Schott 2009). There are indications of wind-forced upwelling at some places along the western boundary of the Bay of Bengal in observations (Murty 1992, Shetye 1991). The Bay has energetic mesoscale eddies and ~500 km vortices with lifetimes of weeks to months in all seasons (Prasanna 2004, Nuncio 2012, Durand 2008, 2009; Chelton 2007). Long-lived cyclonic (upwelling) vortices such as the Sri Lanka dome (Vinay 1998) are candidate sites for surface-forced mixing. However, eddies often have a shallow low-salinity cap particularly in the north Bay, which deters exchange with the subsurface (Nuncio 2012).

9.1.5.2 Hydrological feedback

Bay of Bengal surface water is fresh (**Fig. 39**; Chatterjee 2012) and light due to rain and rivers; one or more intense, shallow haloclines are often seen in CTD and Argo profiles from the north Bay (**Fig. 40**) in summer (Sikka 2000, Bhat 2001), autumn (Sengupta 2008) and winter (Thadathil 2002). In the near-surface ocean, vertical salinity gradients control density stratification, resulting in high gravitational stability. Beyond depths of a few tens of metres, density stratification is generally determined by temperature gradients.

The observed shallow salinity stratification is an indication of weak vertical mixing with saltier water below. Since the early days of Indian ocean observations, there are suggestions that the Bay of Bengal is warmer and less biologically productive than the Arabian Sea partly because fresh, light surface water inhibits vertical mixing with subsurface water (references in Shenoi 2002, Prasanna 2009).

Fig. 39: Summer monsoon (June-September; JJAS) seasonal mean sea surface salinity (g/kg) in the new NIO climatology. From Chatterjee (2012).

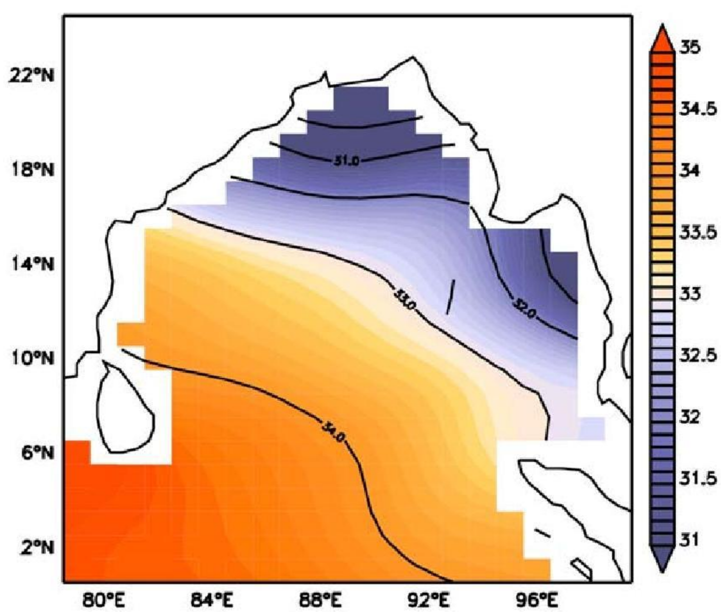
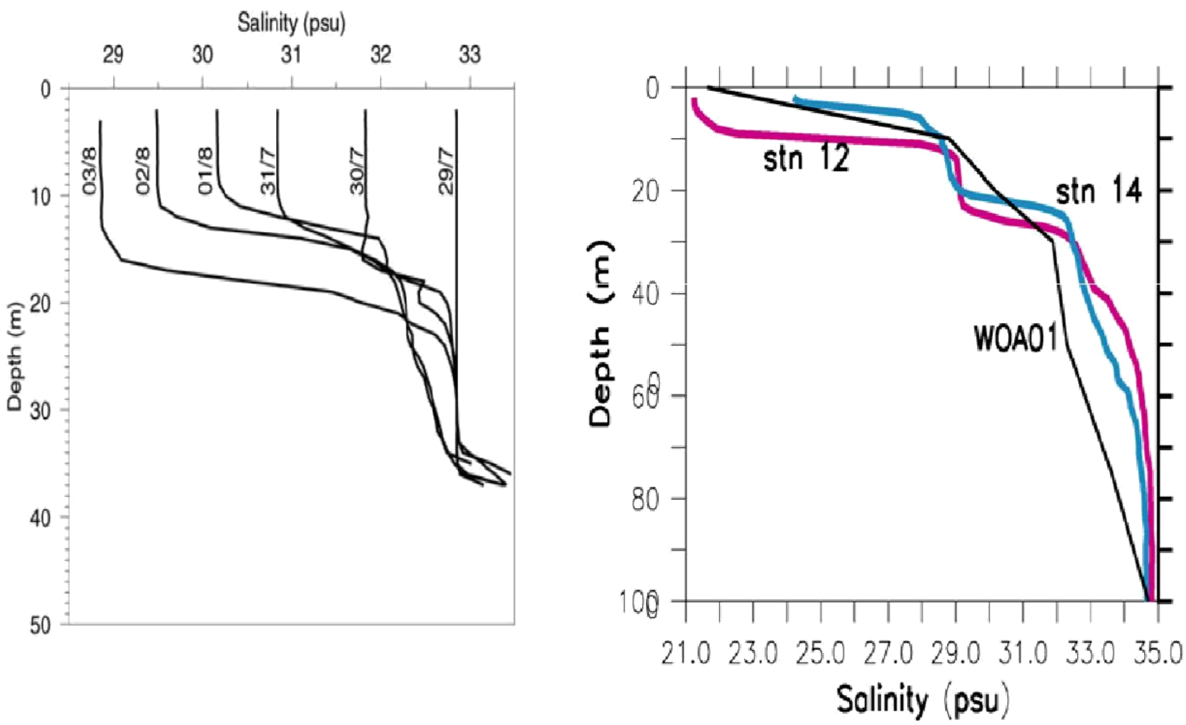


Fig. 40: Shallow haloclines in the north Bay (left) during 29 July -3 August 1999; and (right) at two stations of cruise SK197 in October 2003. [From Vinayachandran (2002).]



Seasonal heat balance suggests a hydrological feedback (Shenoi 2002): Summer monsoon winds cool the Arabian Sea, but cannot break through the surface low-salinity layer in the Bay of Bengal; Bay SST remains warm, supporting monsoon rainfall over both ocean and land (Gadgil 2003); convective heating of the atmosphere in the east sustains strong surface winds in the Arabian Sea; rain and river runoff maintain near-surface stratification in the Bay. This is an interesting hypothesis, although (i) monsoon winds and convection are a response to differential heating of land and ocean, and to convective heating of the atmosphere, on near-planetary scales (Webster 2006), (ii) summer SST is warm over a large region, from the eastern Arabian Sea, through the South China Sea to the western north Pacific, and (iii) the centres of heavy monsoon rainfall are tied to orography, including the Western Ghats and the Burmese mountains (Hoyos 2007; Schott 2009). It is likely that coupling with the relatively small Bay of Bengal basin is more effective on shorter time scales.

Analysis of conventional data indicates that Bay of Bengal river water travels far across the tropical indian ocean within a year (Sengupta 2006) (**Fig. 41**). Models show pathways of river water from the Bay into the Arabian Sea and the South Equatorial Current (Jensen 2001, Schott 2001); long term effects are seen as far as the Pacific (Huang 2010). In principle, river water could influence upper ocean salinity and temperature in remote regions.

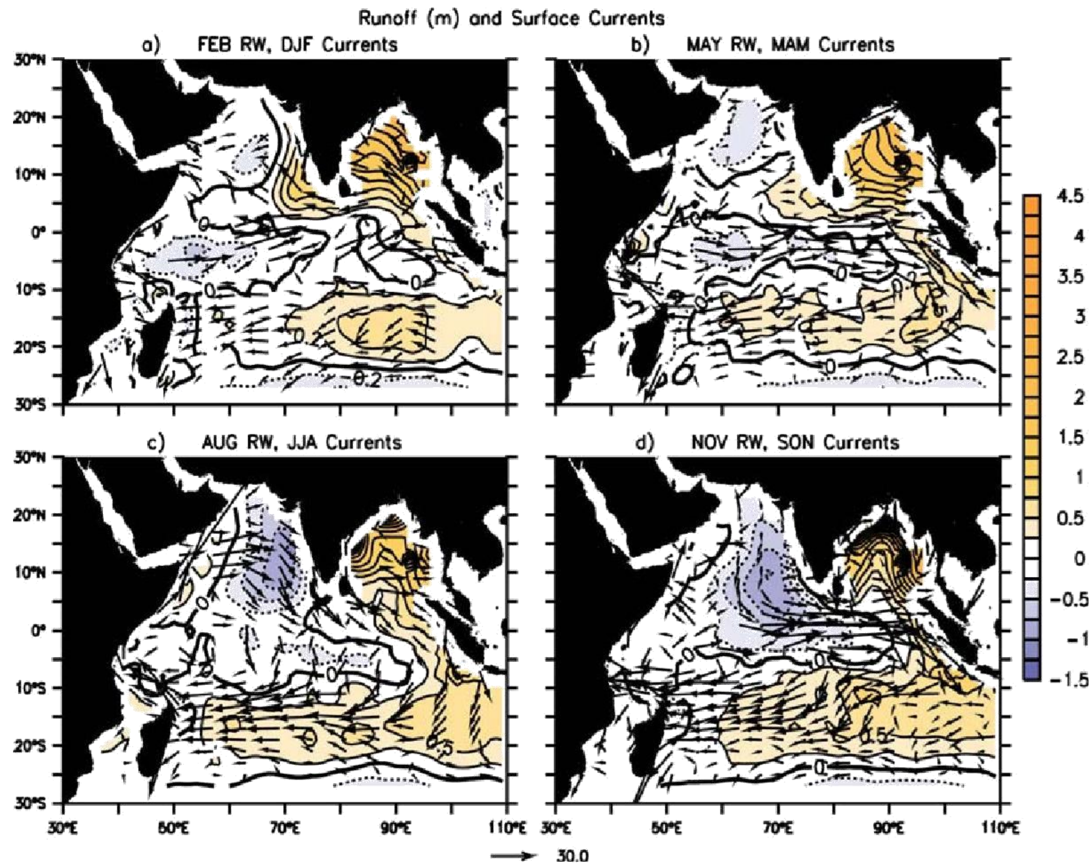


Fig. 41: "River" water (m) in the top 30 m layer in (a) February, (b) May, (c) August and (d) November from the World ocean Atlas 2001; and seasonal upper 15 m velocity from WOCE drifters. [From Sengupta 2006.]

The Bay of Bengal has a barrier layer in most seasons (Rao 2003); barrier layer depth is small in May and reaches 40-50 m in January-March (Thadathil 2007, Mignot 2007). The observed seasonal evolution of the barrier layer is mainly due to surface fresh water from monsoon rainfall and river runoff (Vinay 2002, Bhat 2001) capping the summertime deep warm layer. The shallow, salinity-controlled mixed layer cools in winter due to net surface heat loss, but subsurface warm water is shielded. Moored observations (McPhaden 2009) show that the barrier layer thickness in the middle of the Bay has large amplitude intraseasonal fluctuations associated with thermocline movements forced from the equatorial Indian ocean (Girishkumar 2011).

Large flux of penetrative sunlight below the shallow mixed layer warms the subsurface ocean (Sengupta 2002). Temperature inversions (subsurface warmer than surface) are found in autumn along the east coast of India; inversions of upto 1.5°C are common in the north Bay in December-February (Thadathil 2007; Mignot 2007). If the surface mixed layer were to deepen in winter, entrainment of warm subsurface water would offset cooling due to surface heat flux (de Boyer 2007).

A test of hydrological feedback using a regional coupled model (Seo 2009) shows that river runoff leads to shallow mixed layers but only localised warming of summer SST in the north Bay. In winter, the presence of river water leads to extensive SST cooling in the north Indian ocean, and a wamer subsurface layer. Winter SST is cooler (upto 3°C in the north Bay) relative to an experiment with no river runoff although evaporation is reduced, because (i) surface heat loss affects a shallower layer, and (ii) the halocline suppresses mixing with warmer subsurface water. Summer rainfall is not changed significantly, but winter rainfall is higher due to enhanced convergence of northeasterly winds south of the equator.

9.1.5.3 Monsoon Intra-seasonal oscillations (ISO)

The Indian summer monsoon has an "active-break" cycle, with sub-seasonal dry and wet spells (**Fig. 42**). An irregular oscillation with a mean period of 30-40 days is associated with a band of organised convection moving north from the equatorial Indian Ocean (10°-5°S) to the north Bay of Bengal/India (25°N) at about 1 degree latitude per day (Sikka 1980; Yasunari 1980). Several theories or models have been proposed to explain the 30-40 day northward propagating mode (often called the 30-60 day mode or boreal summer ISO): They include (i) mainly dynamical mechanisms involving interaction of convection with large-scale monsoon wind shear, (ii) models where feedback from surface turbulent and radiative fluxes are important, and (iii) models that include coupling with the ocean. See Krishnamurti (1998) for an early suggestion of air-sea coupling on ISO scales through surface fluxes, Jiang (2004) for a dynamical mechanism, Chou (2010) for an evaluation of different mechanisms; and Schott (2009), Sobel (2009), Hendon (2011), Wang (2011) and Goswami (2011) for recent reviews.

A prominent "quasi-biweekly" mode (period 10-20 days) appears in surface pressure and rainfall over the northern Bay of Bengal. The 10-20 day period is prominent in rainfall over Bangladesh and northeast India, and is linked to southward propagation of convective activity east of Tibet (Fujinami 2011, Kikuchi 2009). The tropical quasi-biweekly mode moves west from the west Pacific or South China Sea to the central Bay of Bengal and India. This mode is an important modulator of south Asian monsoon rainfall (Murakami 1976, Krishnamurti 1980, Chatterjee 2004, Goswami 2012). It has many characteristics of moist equatorial Rossby waves with two counter-rotating vortices on either side of the equator, except that the line of symmetry lies to the north (see below). We do not discuss interannual variability here, but note that Indian monsoon droughts are marked by unusually long subseasonal dry spells; some long dry spells are linked to the arrival of Rossby waves from the east Pacific (Neena 2011; Roundy 2004).

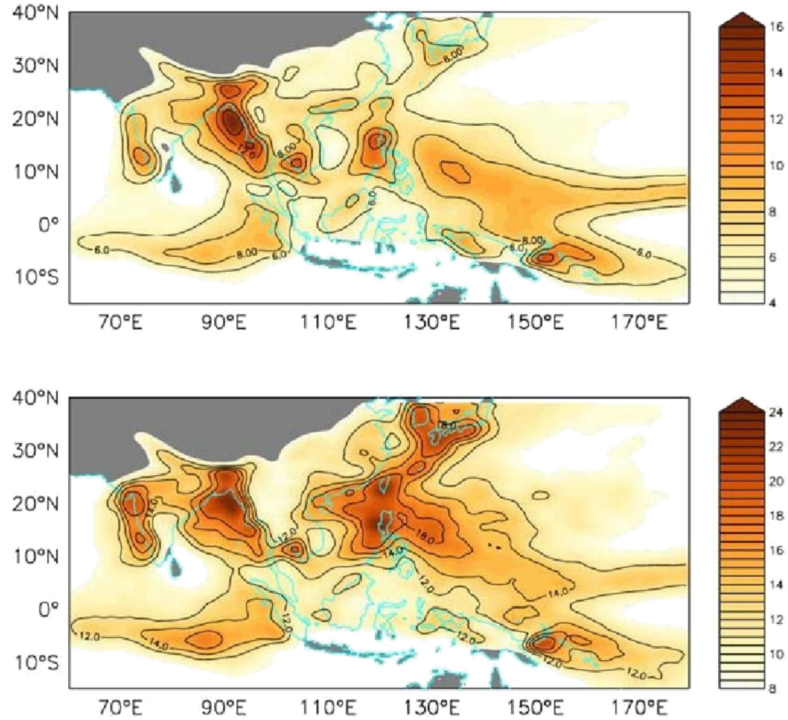


Fig. 42: Climatological mean summer (JJAS) rainfall (mm/day) and daily standard deviation of 10-90 day filtered rainfall (mm/day; lower panel) from daily TRMM multi-satellite precipitation analysis, 1998-2007.

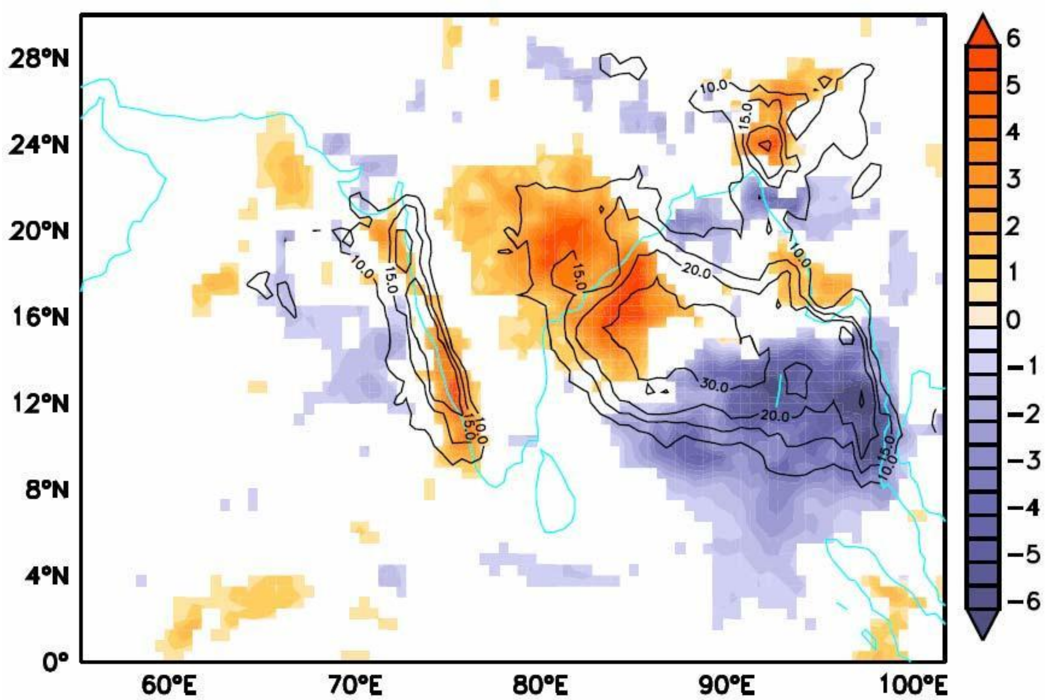


Fig. 43: Composite heavy monsoon rainfall (R; contours in mm/day) over the central Bay of Bengal (12-17°N) and rate of change of rainfall (dR/dt; shades). The composites are based on about 120 heavy rain days in 10 monsoon seasons.

The structure and movement of organised rainfall can be visualised directly from rainfall (R) and rate of change of rainfall (dR/dt). We created a 10-year (1998-2007) summer monsoon composite of heavy rainfall over the central Bay of Bengal from daily TRMM Multisatellite Precipitation analysis (TMPA). The R composite shows the familiar tilted monsoon rainband or ITCZ (Webster 2006), while the dR/dt composite shows rain rate increasing in the north and west, and decreasing in the southeast (**Fig. 43**). In other words, organised rainfall "moves" to the northwest at about 6 m/s. Lagged composites show that in some respects the associated circulation resembles the moist Rossby waves of the biweekly mode (Chen 1993), with 6000-8000 km wavelength (**Fig. 44**). As the two counter-rotating vortices move north, the line of symmetry moves north due to the background vorticity associated with the large-scale monsoon flow (Chatterjee 2004, Kikuchi 2009).

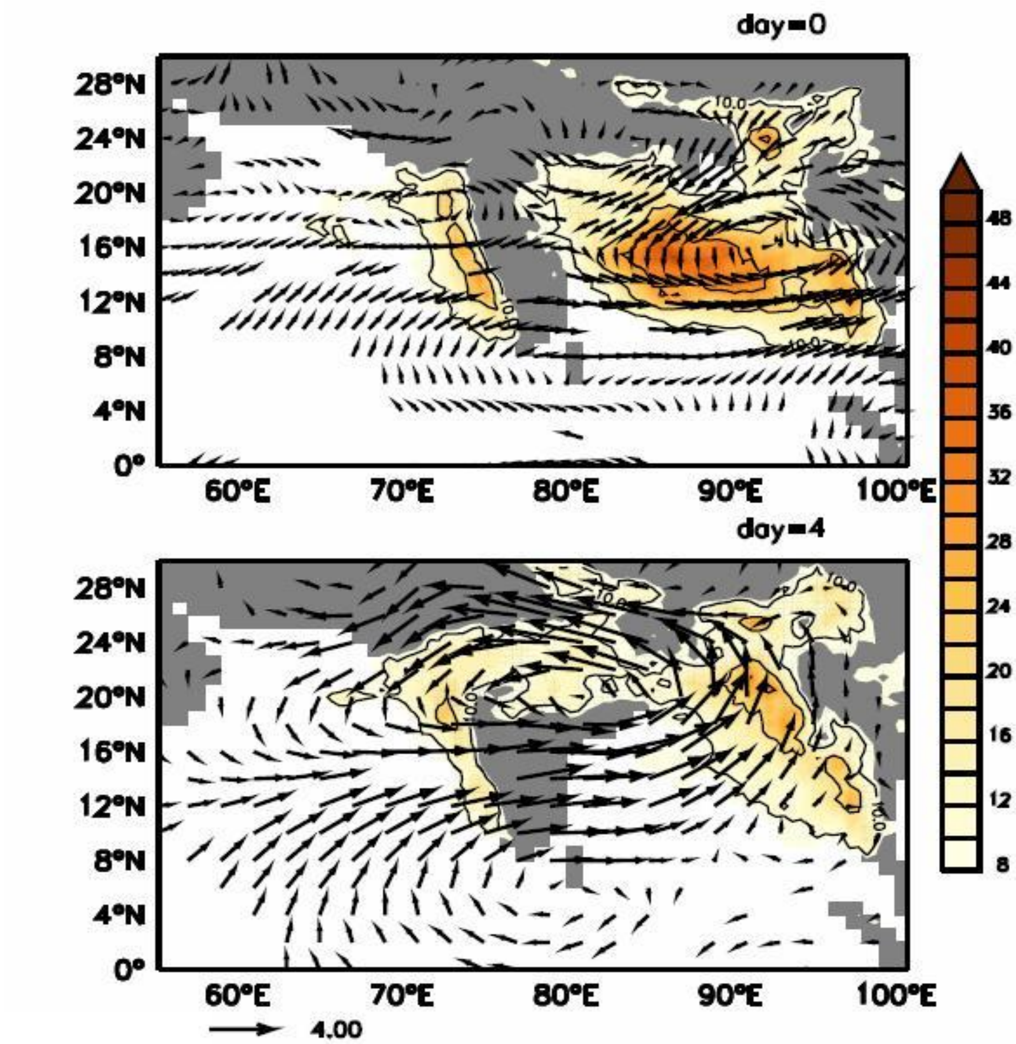


Fig. 44: Composite rainfall (mm/day) as in Fig. 43, and 850 mb wind anomalies on (top) day 0, and (bottom) day 4.

The mean recurrence time of the daily R and dR/dt patterns is about 35 days. If dR/dt is slightly smoothed to suppress synoptic scales, a slow time-scale is evident. A tilted rain-band with zonal scale of about 10000 km and centres of heavy rainfall moves parallel to itself (**Fig. 45**) with northward speed of about 1 m/s**.** The slow evolution resembles the 30- 40 day mode of the south Asian monsoon (Goswami 2011), and is consistent with the "northeastward" propagating mode documented in Wang (2006) over a wider domain

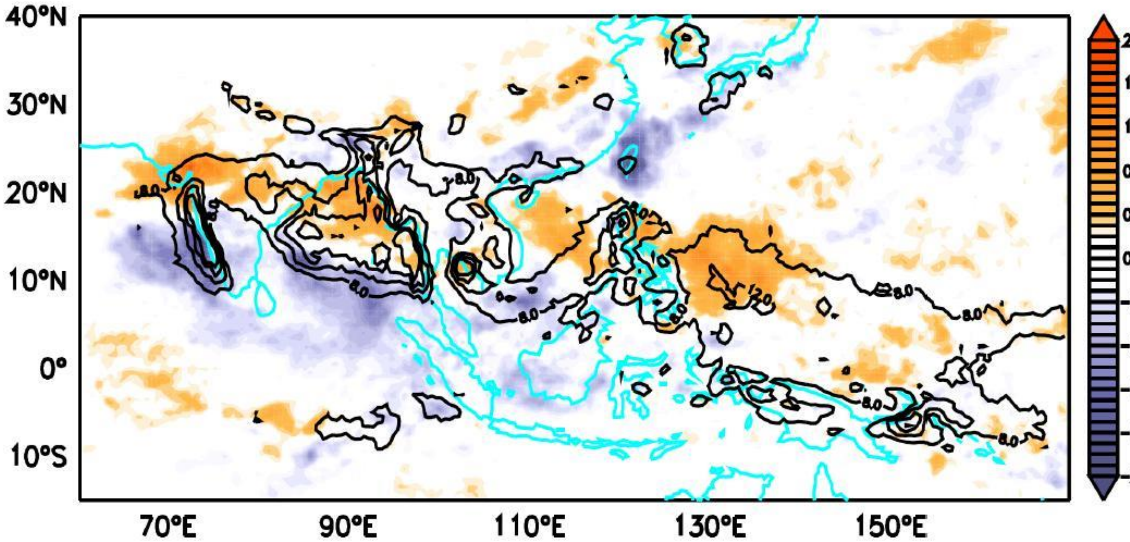


Fig. 45: Composite rainfall and dR/dt, as in Fig. 12 but smoothed using a seven-day running mean.

The 2003-2008 composite vertical structure of humidity and temperature from the Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit on the Aqua satellite (AIRS for short) are in broad agreement with radiosonde observations during active and quiet periods of monsoon convection over the Bay. The composite heavy rainfall over the central Bay and the corresponding humidity (q) and temperature (T) anomalies (seasonal cycle removed) are shown in **Fig. 46.** The 925-400 mb layer is moist in the presence of rain, with the largest positive q at 500-600 mb; south of the rain the atmosphere is dry upto the 500 mb level, but the largest negative q is at 850 mb; the near-surface layer under heavy rain is dry, perhaps due to downdrafts.

The 700-300 mb layer is warm and the boundary layer is cool in the rainy region due to radiative effects and elevated latent heating. North of the heavy rain, the vertical structure of T anomaly is reversed. In this region the boundary layer is warm and moist, likely due to shallow convection, gradually destabilising the atmosphere. The boundary layer is dry to the south of the rainy region, and rainfall decreases. The increase of rainfall in the north and decrease to the south is manifested as northward "propagation". These composites are qualitatively similar to the sequence of events involved in eastward propagation of MJO (Tian 2010; Kiladis 2009).

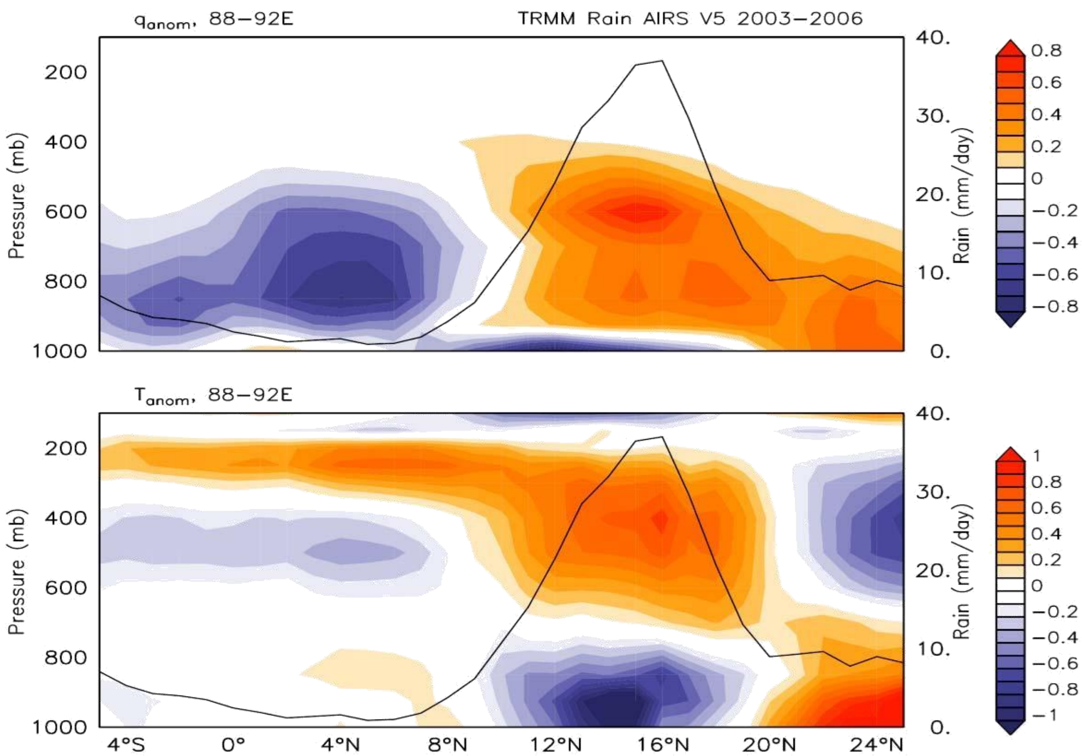


Fig. 46: Pressure-latitude section of AIRS specific humidty (q, top) and air temperature (T, bottom) anomalies, and latitudinal variation of rainfall (mm/day, black line) on day 0 of the central bay heavy rain composite.

9.1.5.4 Surface fluxes and SST

As mentioned earlier, a central question in monsoon air-sea interaction is why Bay of Bengal SST remains warm despite strong monsoon winds and reduced surface sunlight due to frequent deep convection from mid-May to mid-October. Surface fresh water may be one reason, but the atmosphere has an important role as well. Observations show that the near-surface layer of the monsoon atmosphere has some special features. Sea-air temperature and specific humidity differences in the north Bay of Bengal are much smaller than in the west Pacific, although the two regions have comparable SST (**Fig. 47 a,b**). Wind speed in the north Bay varies from under 2 m/s during breaks to over 15 m/s during active monsoon conditions. The typical wind speed is 6 m/s in the dry phase of the monsoon, and 12 m/s in the active phase (**Fig. 47d**). The small sea-air differences of humidity and temperature affects air-sea fluxes. For a given wind speed, latent heat flux Q_{lat} is low compared to nearby ocean basins (**Fig. 48**).

The reasons for low sea-air differences are not understood, but they are likely to be related to the structure and dynamics of the atmospheric boundary layer (ABL) in this small basin surrounded by land on three sides. On the other hand, surface fluxes have direct influence on the properties of the ABL. In the summer monsoon season,

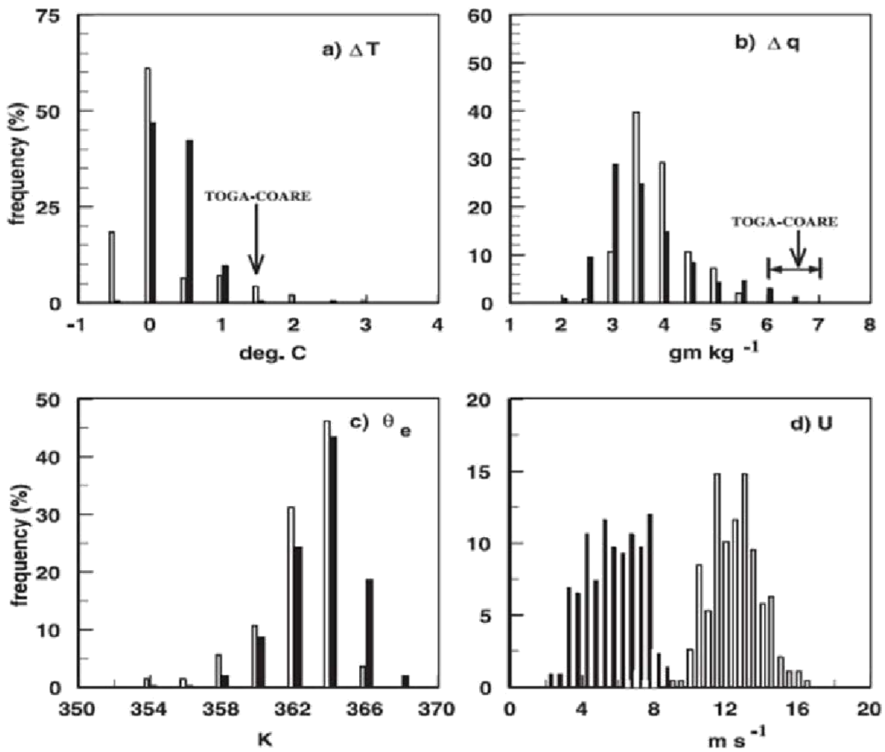


Fig. 47: Frequency distribution (July-August 1999, north Bay, BOBMEX) of (a) se-air temperature difference (b) sea-air specific humidity difference, (c) equivalent potential temperature at 10 m, (d) windspeed at 10 m; filled bars correspond to break conditions, and open bars to active convection. From Bhat (2003).

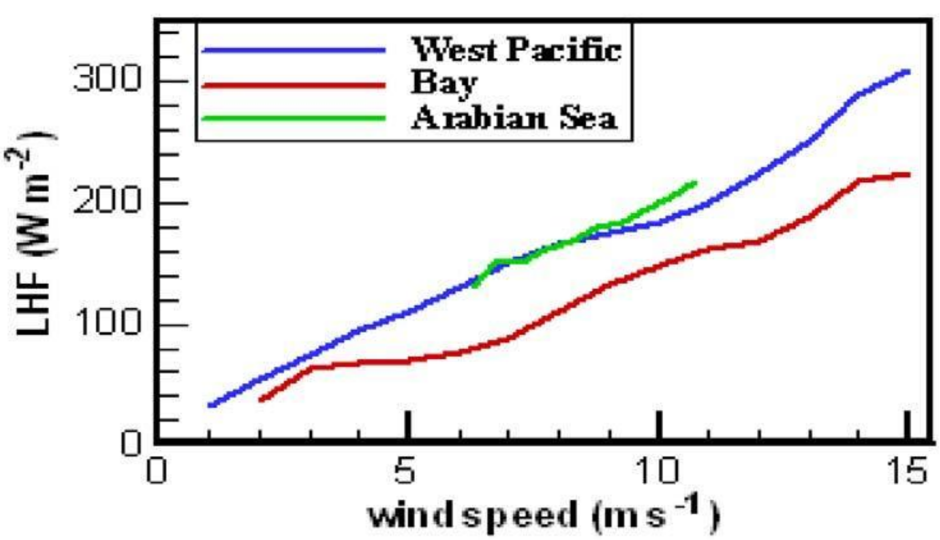


Fig. 48: Windspeed dependence of latent heat flux in the north Bay of Bengal (BOBMEX), compared to the west Pacific (TOGA-COARE) and the Arabian Sea.

we expect large differences in atmospheric properties between the convective north Bay and the drier southern Bay. There is need for detailed observations of surface fluxes, the near-surface layer of the atmosphere and the ABL in different regions. Given the unique environment of the Bay, bulk flux formulations under low and high wind regimes, and unstable and stable conditions, need to be validated.

The north Bay of Bengal has large amplitude SST ISO during the summer monsoon season; SST variability is smaller in the south. Net surface heat flux fluctuates between + 80-120 W/m^2 under clear, low wind conditions (break monsoon) and – 80-120 W/m^2 during cloudy, windy periods (active monsoon) (Webster 2002, Bhat 2001). The one-dimensional heat balance for a mixed layer of depth H is

$$\rho C_p H\, \partial SST/\partial t = Q_{net} - Q_{pen} + \text{Advection} + \text{Mixing}$$

where rho is density of seawater, C_p is specific heat, and Q_{pen} the flux of penetrative shortwave radiation at depth H. For fixed H and periodic heat flux, SST lags flux by a quarter cycle; the amplitude of SST oscillation is inversely proportional to forcing frequency, i.e. SST responds selectively to longer periods present in the forcing. On the other hand, it is possible that the large -amplitude (~1^{o}C) SST ISO in the north Bay directly influences surface turbulent fluxes (Krishnamurti 1998) and local stability of the atmospheric boundary layer, thereby modulating convection.

Observations from a four-ship polygon in the Bay during the monsoon experiment MONEX 1979 first revealed the importance of near-surface salinity and optical properties of seawater in subseasonal SST evolution (Moshonkin 1991). Near-surface salinity was low at 18^{o}N, and optical attenuation coefficient was 3-4 times higher than at 14^{o}N, suggesting the presence of turbid river water in the north. The authors found that realistic simulation of SST evolution cannot be achieved without accounting for the effects of surface fresh water and water clarity.

Since MONEX, several studies using observations and models have shown that ISO of summer SST in the northern and central Bay of Bengal is mainly a response to heat flux (Sengupta 2001, Schiller 2003, Roxy 2007, Han 2006, Parampil 2010), while ocean processes (advection, entrainment, mixing) dominate in the western and northern Arabian Sea (Vialard 2011). Space-time observations of upper ocean optical properties would be specially useful in the monsoon season, when clouds limit satellite capabilities.

We created daily surface heat fluxes for 2003- 2007 in the tropical Indian Ocean from satellite data, including QuikSCAT winds, ISCCP radiation and AIRS humidity and temperature, calibrated against RAMA bouy observations (McPhaden 2009). The amplitude of net surface heat flux ISO in the summer monsoon is about 90 W/m^2 over the Bay of Bengal (**Fig. 49**).

It is interesting that the contribution of sub-seasonal variations of surface humidity and air temperature to latent heat flux is comparable to the effect of wind speed variations **(Fig. 50)**. The q and T fluctuations are not simply related to variations in surface winds blowing from land; subsidence and entrainment of dry air at the top of the boundary layer could be important as well.

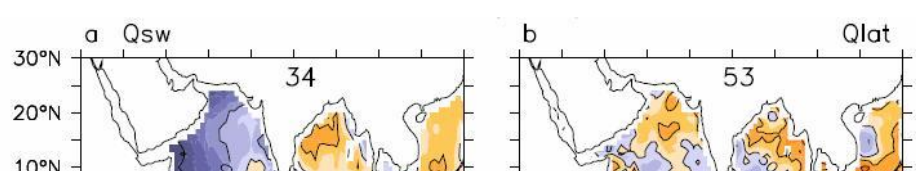


Fig. 49: Amplitude of sub-seasonal (10- 60 day) surface flux variations (W/m^2) (a) shortwave radiation, (b) latent heat flux, (c) net long wave radiation and (d) net heat flux, summer monsoon season.

Penetrative shortwave radiation flux across the mixed layer base is estimated from satellite chlorophyll and mixed layer depth from Argo floats (de Boyer 2004). SST ISO in the Bay of Bengal and eastern Arabian Sea is mainly forced by heat flux ($Q_{net} – Q_{pen}$) in May-October. Elsewhere ocean processes dominate SST evolution (**Fig. 51).** In November-April SST ISO is mainly a response to heat flux in the central and eastern equatorial Indian Ocean. Thus on sub-seasonal scales the evolution of SST is coherent with surface fluxes only in regions of organised deep convection (monsoon, ITCZ), evidence for the active role of surface fluxes in air-sea coupling (Sobel 2008, 2010). Note from equation (1) that SST alternately cools and warms in response to heat flux only if $Q_{net} – Q_{pen}$ changes sign on intra-seasonal scales (as episodes of organised deep convection pass overhead).

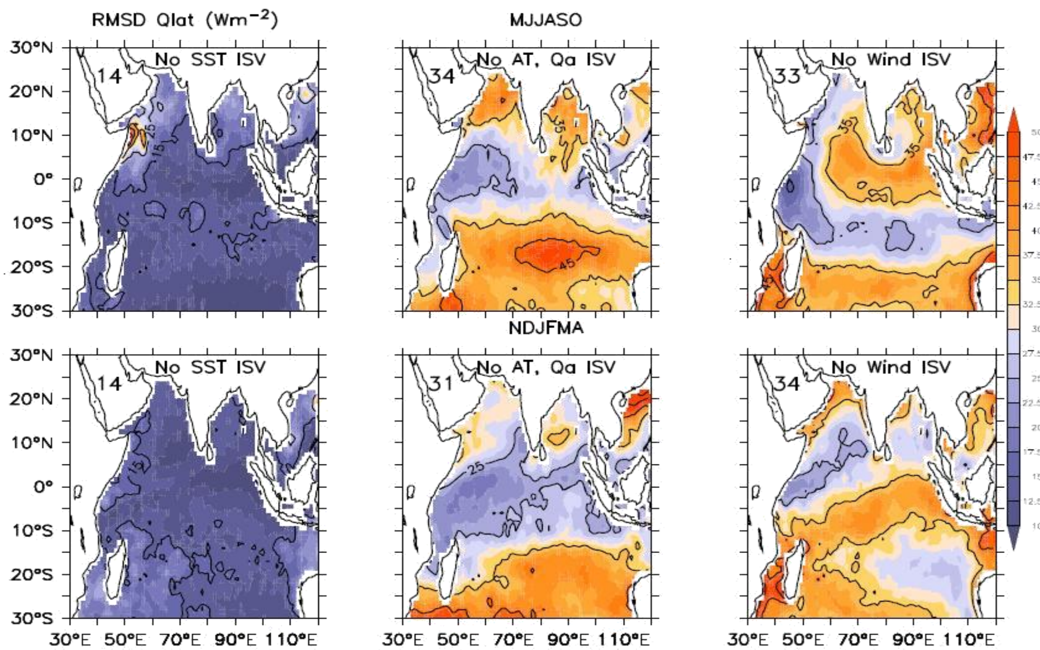


Fig. 50: Change in 10-60 day variability of latent heat flux due to (left) SST ISO, (centre) air temperature and specific humidity ISO, and (right) windspeed ISO. The top and bottom panels are for May-October and November-April, 2003-2007.

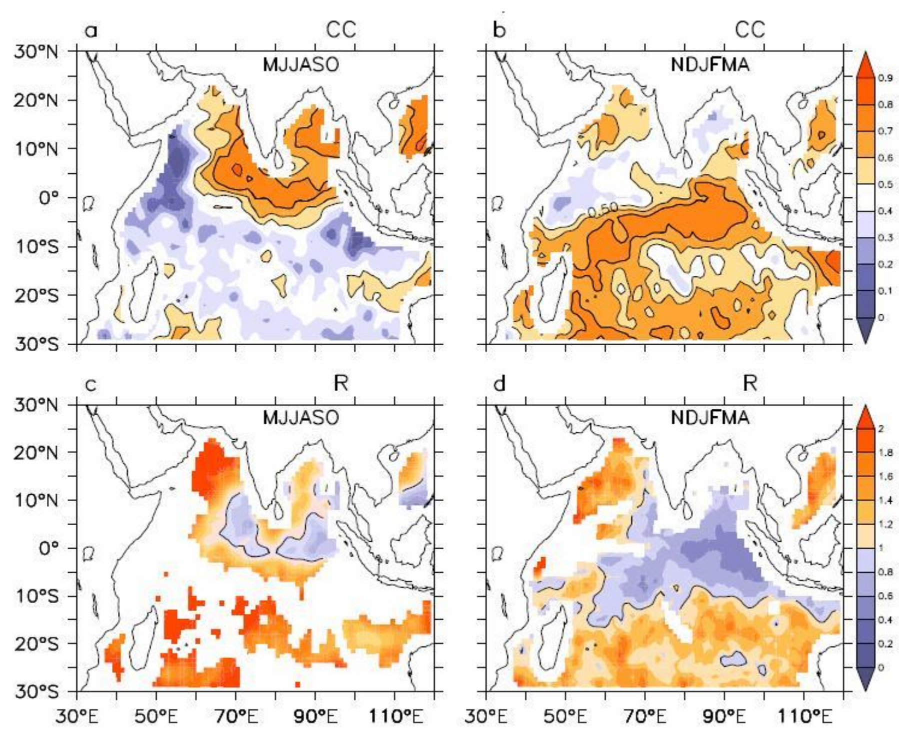


Fig. 51: Correlation (CC) between 10-60 day heat flux and rate of change of SST (top) and ratio (R) of heat flux forcing to SST response. Fluxes drive SST where CC is high and R is close to 1. From Parampil (2011).

9.1.6 Coupled monsoon ISO

9.1.6.1 The atmosphere

A synthesis of surface, upper air and satellite observations suggests a view of the 30 -60 day eastward moving Madden- Julian oscillation (MJO) as a self-regulating oscillator. The MJO has three phases over the Indo-Pacific warm pool: "(i) the destablization phase: the atmosphere becomes increasingly unstable by the combination of radiative cooling of the upper troposphere, the gradual build up of shallow convection, and the warming of the SSTs under near-clear-sky and calm conditions; (ii) the convective stage: large-scale convection develops over the region resulting in widespread heavy precipitation, deepening of the oceanic mixed layer, cooling of the SST, and moistening of the upper troposphere; and (iii) the restoring phase: the combination of continued cooling of the SSTs maintained by the strong low-level winds and reduced solar heating, with the radiative heating of the upper atmosphere by high clouds sustained by high humidity, are major factors in stabilizing the atmosphere, suppressing convection, bringing an end to the cooling of the SSTs, and eventually leading to a calming of the winds, dissipation of the thick upper-level clouds, and a restoration of the cycle to its warming phase" (from Stephens 2004).

The large-scale physical setting in which summer monsoon ISO move north over the Indian subcontinent and the Bay of Bengal is distinct in many respects. First, the monsoon circulation has large easterly shear, with south-westerlies at low levels and the tropical easterly jet aloft; monsoon flow is so strong that it modifies the ambient potential vorticity field. Secondly, the western Ghats and the Burmese (Myanmar) mountains anchor heavy, persistent orographic rainfall in the eastern Arabian Sea and eastern Bay of Bengal (Xie 2006; **Fig. 42**).

Finally, it is important to note that (i) low level monsoon winds are associated with significant positive vorticity and horizontal convergence over the north Bay, and (ii) seasonal mean distribution of thermodynamic fields have north-south gradients in the south Asian monsoon region. Upper tropospheric temperature and low-level entropy are highest over India and the north Bay of Bengal, just south of the Himalayas (Boos 2010); column-integrated water vapour (precipitable water) also has a maximum (~60 kg/m^2) over the north Bay of Bengal and adjoining land, giving significant gradients between the equatorial Indian Ocean and north India/north Bay. A tongue of cool SST lies just south of the Bay of Bengal in summer, mainly due to advection of upwelled water by the eastward summer monsoon current (Vecchi 2002, Joseph 2005), so summer SST has a gradient between the north-central Bay and the cool tongue.

The first reliable daily SST data from satellite microwave sensors showed that cool SST in the Bay precedes monsoon breaks by 7-10 days (Vecchi 2002). SST

ISO in the north Bay has larger amplitude than in the south, as pointed out earlier. Sub-seasonal events of monsoon convection over the central Bay tend to occur about a week after the meridional SST gradient (north warmer than south) exceeds 0.75^{o}C (Shankar 2007).

On intra-seasonal scales, the lowest OLR (or heaviest rain) is not over the warmest SST, but a few degrees to the south (Fu 2003). In other words, SST leads convection by about a week. The structure and northward movement of summer monsoon ISO in convection, wind speed, surface heat flux and SST are coherent, suggesting air-sea interaction (Sengupta 2001b).

Based on the premise that warm SST is associated with low sea level pressure (SLP; Lindzen 1987), Vecchi and Harrison (2002) offered a coupled oscillator mechanism (**Fig. 52**): A meridional SLP gradient exists because of the cool tongue south of the Bay. Warm SST in the north Bay reduces land-sea pressure difference, weakening the winds in the north, but strengthening zonal winds in the southern Bay. The north Bay warms, but the southern Bay cools due to enhanced evaporation, cloudiness and vertical mixing, thus increasing pressure gradient and winds in the central Bay. The central Bay cools, and the region of enhanced SST/SLP gradient moves north. Eventually north Bay SLP returns to normal, SST cools and the SLP gradient disappears. Under low winds and reduced cloudiness, Bay SST warms, setting up the basin-scale meridional SLP gradient once more.

Northward propagation of the monsoon rainband with weaker westerlies warming SST to the north and stronger westerlies cooling SST to the south is consistent with wind-evaporation-SST feedback (Xie 1999; Schott 2009). In addition, clouds lead to 50-60 W/m^2 variation in surface shortwave flux on ISO scales (see **Fig. 50**), as mentioned earlier.

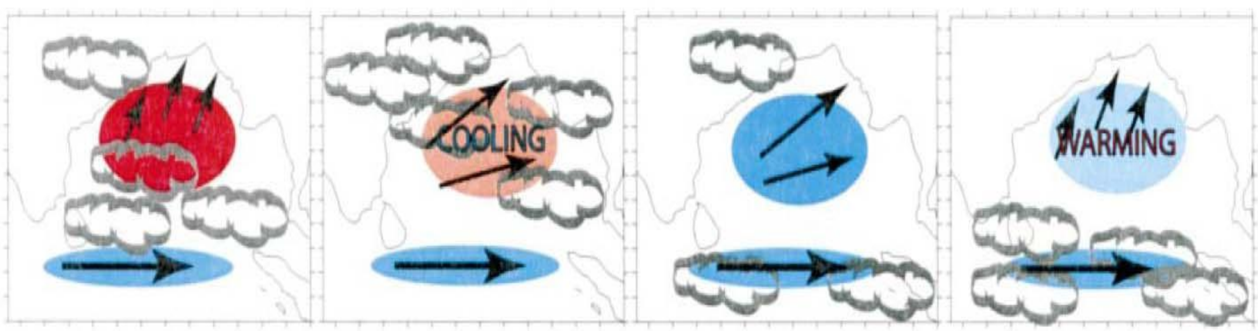


Fig. 52: Coupled oscillator mechanism for monsoon ISO. From Vecchi 2002.

High monsoon clouds with large optical depth over the Bay of Bengal and adjoining land give net negative cloud forcing at the top of the atmosphere (Rajeevan 2000), i.e. the cloud albedo effect is larger than the cloud greenhouse effect. We have mentioned that the north Bay has very high seasonal mean column water vapour in summer. The net radiative effect of clouds and water vapour can influence column stability by cooling the surface and warming the atmosphere. Spencer (2007) studied radiative changes on ISO scales from daily satellite observations of tropospheric temperature, clouds and rain over the global tropical oceans (20^{o}S-20^{o}N). They found that the warm and rainy phase of the composite ISO is characterised by a net reduction of radiative (shortwave plus longwave) energy input to the ocean-atmopshere system.

9.1.6.2 The subsurface ocean

Krishnamurti (2007) used global Argo temperature data to create initial conditions with coupled data assimilation in an ensemble forecast experiment from June to August 2004. They found enhanced prediction skill of MJO, summer monsoon ISO and central India monsoon rainfall, probably due to improvement in tropical SST.

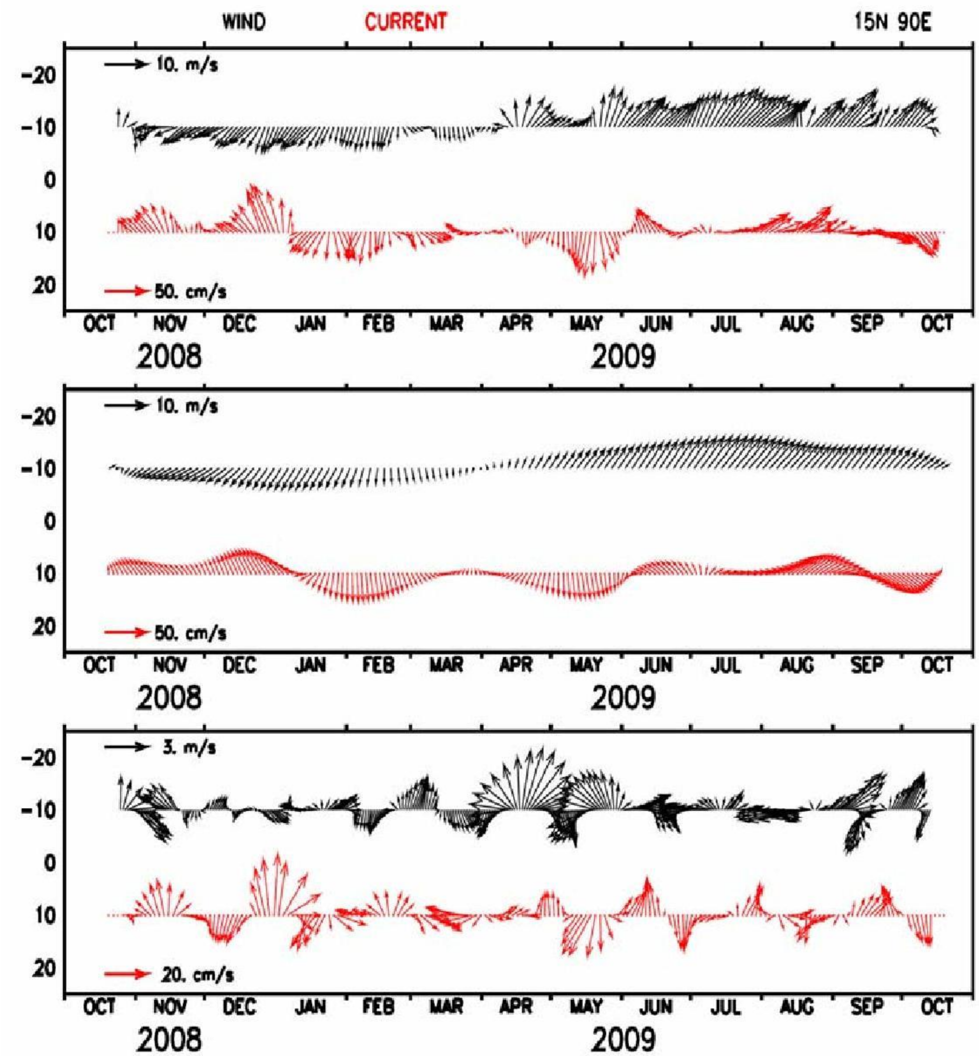
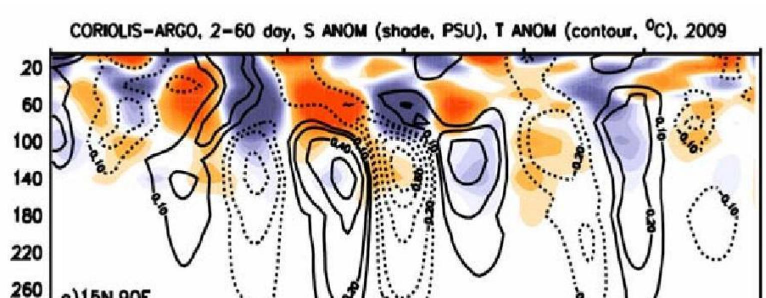


Fig. 53: Daily Scatterometer winds and10m currents from RAMA mooring at 15°N, 90°E (top panel). Sub-seasonal cycle of winds and currents (middle), and sub-seasonal (10-60 days) winds and currents.

We examined ISO in one year of daily ocean observations from the RAMA mooring at 15°N, 90° E in the Bay of Bengal (McPhaden 2009) by separating time scales greater than 90 days (i.e. the seasonal cycle) from subseasonal variability. The seasonal cycle of scatterometer winds is dominated by one-year period, but 10 m currents indicate linear long Rossby waves with period of about 120 days (**Fig. 53**). These waves are likely to originate in the equatorial Indian ocean: In a typical year, organised convection is located over the eastern equatorial Indian ocean in April- May, October-November and during the summer monsoon. Westerly wind stress peaks three times a year in a Matsuno-Gill response, forcing equatorial jets and downwelling Kelvin waves (Wyrtki 1973, McCreary 1993; Senan 2003, Webber 2012). Note that in general the current does not appear to be dominated by Ekman response to the local wind on any time scale.



a

b

c

Fig. 54: Equatorial forcing of subseasonal signal in the Bay. Subseasonal S (shade) and T (contour) from the CORIOLIS gridded ARGO dataset, at 15ºN,90ºE (top), 18ºN,93ºE (middle) and 4ºN,95ºE (bottom). The panel on the right shows the propagation of the signal from point c to b to a.

Subseasonal (10-60 day period) near-surface currents show waves or eddies throughout the year with a characterstic time scale of 45-50 days. Satellite sea surface height shows eddies arriving at the 15 °N mooring from the eastern boundary of the Bay. Their origin can be traced to wind-forced ISO in the eastern equatorial Indian ocean (Masumoto 2005; Sengupta 2007; Girishkumar 2011). Argo data indicate that the subseasonal signal in T and S moves north along the eastern boundary of the Bay (**Fig. 54**) and arrive at the 15°N mooring from the northeast. We note that this observed signal is inconsistent with a prediction of linear wave theory: A coastal Kelvin wave moving north along the eastern boundary cannot radiate Rossby waves to the interior once it crosses a critical latitude (Vialard 2009). The critical latitude depends on wave period; for a Kelvin wave speed of 2.6 m/s (Chelton 1998), the critical latitude for 60-day period is about 10°N.

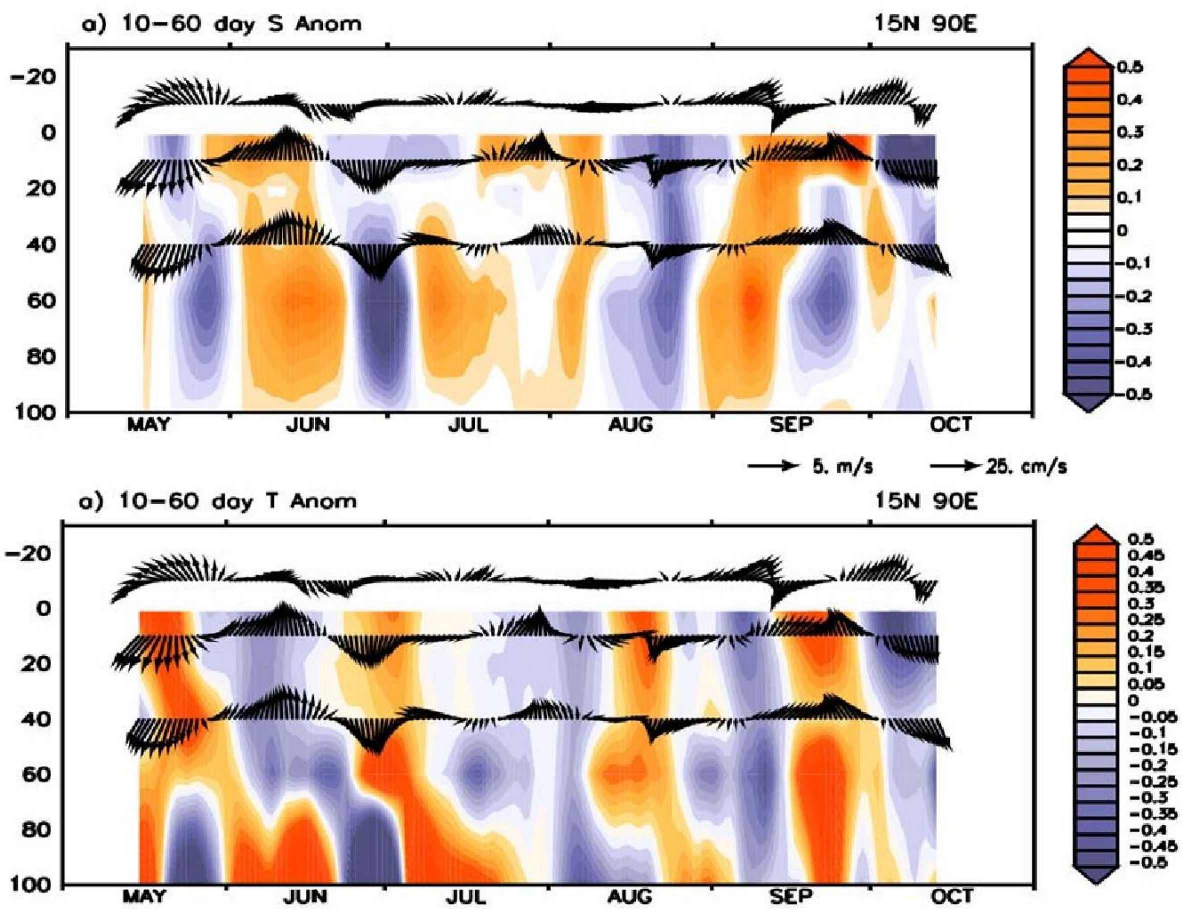


Fig. 55: 10- 60 day subsurface salinity (top panel; shades), and temperature (bottom) for summer 2009, overlaid with 10-60 day current vectors at 10 m and 40 m depth, from the RAMA mooring at 15oN, 90oE; 10-60 day scatterometer wind si also shown.

The ISO of 10 m and 40 m currents are very similar, suggesting mainly geostrophic flow in the upper ocean. ISO of 10 m currents appear to be related to ISO of near-surface salinity at the 15°N mooring in the summer of 2009 (**Fig. 55**) - the upper 20 metre layer is fresher when the flow is from the north and saltier when the flow is from the south, implying advection of a north - south salinity gradient. Analysis of Argo data from the central Bay has shown that sub-seasonal variation of near-surface salinity is not a response to local P-E. Salinity ISO appear to be dominated by advection in the presence of large gradients, consistent with the notion that river water moves in lenses or filaments (**Fig. 56** ; Parampil 2010). Salinity variation at 60 m depth has amplitude of 0.4-0.5 g/kg, but is distinct from near-surface changes. Temperature ISO have complex vertical structure, with largest amplitude at about 100 m depth, at the surface, and at 60 m. Unlike salinity ISO, SST ISO are probably forced by surface fluxes – they are not closely related to the ISO of currents.

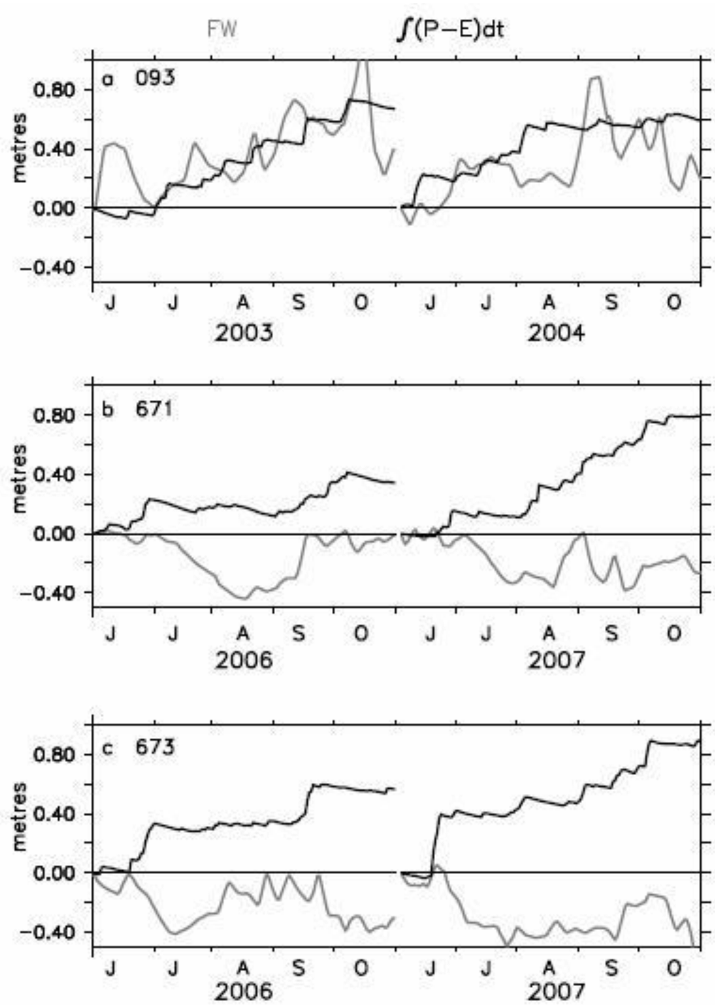


Fig. 56: Response of upper 30 m freshwater content (FW) to surface freshwater forcing (P-E) in the monsoon season. Salinity data are from three Argo floats (093, 671 and 673) in the central Bay with 5-day sampling; The evolution of FW (grey) is shown together with the time integral of P-E (bold; both quantities are set to zero on 1 June). From Parampil 2010.

9.1.6.3 Coupled models

Several studies with general circulation models (GCM) adopt the following strategy to elicit the role of air-sea coupling in ISO: Time-varying SST from a coupled model simulation is prescribed as lower boundary condition for the stand-alone atmosphere model; differences between ISO in the atmosphere model and the coupled model are attributed to air-sea interaction. Although most coupled models have SST biases and deficiencies in representation of summer monsoon ISO, this class of experiments indicates that coupling leads to more realistic ISO over the Bay of Bengal and the Indian subcontinent (Zheng 2004, Rajendran 2006, Lau 2012).

Two recent studies (Goswami 2012; DeMott 2011) use an atmosphere model with sophisticated treatment of convection, embedding cloud resolving models at several points in each grid box of the GCM. When this model is coupled to an ocean GCM, there is marked improvement in the space-time characteristics of tropical intraseasonal oscillations, including northward propagating summer monsoon ISO. Within the coupled model there is at least one mechanism of air-sea interaction, which the stand-alone atmospheric GCM lacks. It is likely that the coupling mechanisms (feedback loops) in climate models are complex and model-dependent. Observations of physical processes will be crucial to develop new concepts about basin-scale air-sea interaction towards better prediction of monsoon ISO.

9.1.7 Upper ocean physics from moored observations

In preparation for this programme, a mooring was designed and deployed by INCOIS, PMEL, IISc and NIOT at 18°N, 89.5°E, about 500 km from the mouth of the Meghna. Temperature (T) and salinity (S) sensors at 1, 7, 15, 25, 50 and 100 m depth, and an acoustic Doppler current meter at 5 m depth recorded 5-minute averages every 10 minutes from November 2009 to November 2010. We discuss the high-frequency observations from this mooring in some detail because they suggest possible lines of enquiry in the study of upper ocean physical processes.

Near-surface temperature cools in winter and warms in spring; summer cooling is relatively small. 50 m T is generally warmer than 1m T (SST) in December 2009-January 2010 (**Fig. 57 A**). Surface salinity (SSS) is low (33 g/kg or less) in September 2010, but also in November 2009 -March 2010. We made simple estimates of the near-surface salinity response to local rainfall based on data during an isolated 100 mm/day rain event in late May (**Fig. 57 B)** The estimates show that the 0.1-1.0 g/kg salinity fluctuations with periods of days to weeks during the monsoon season are not a direct response to rain; they are likely due to advection of river and rain water in the presence of lateral salinity gradients (Parampil 2010).

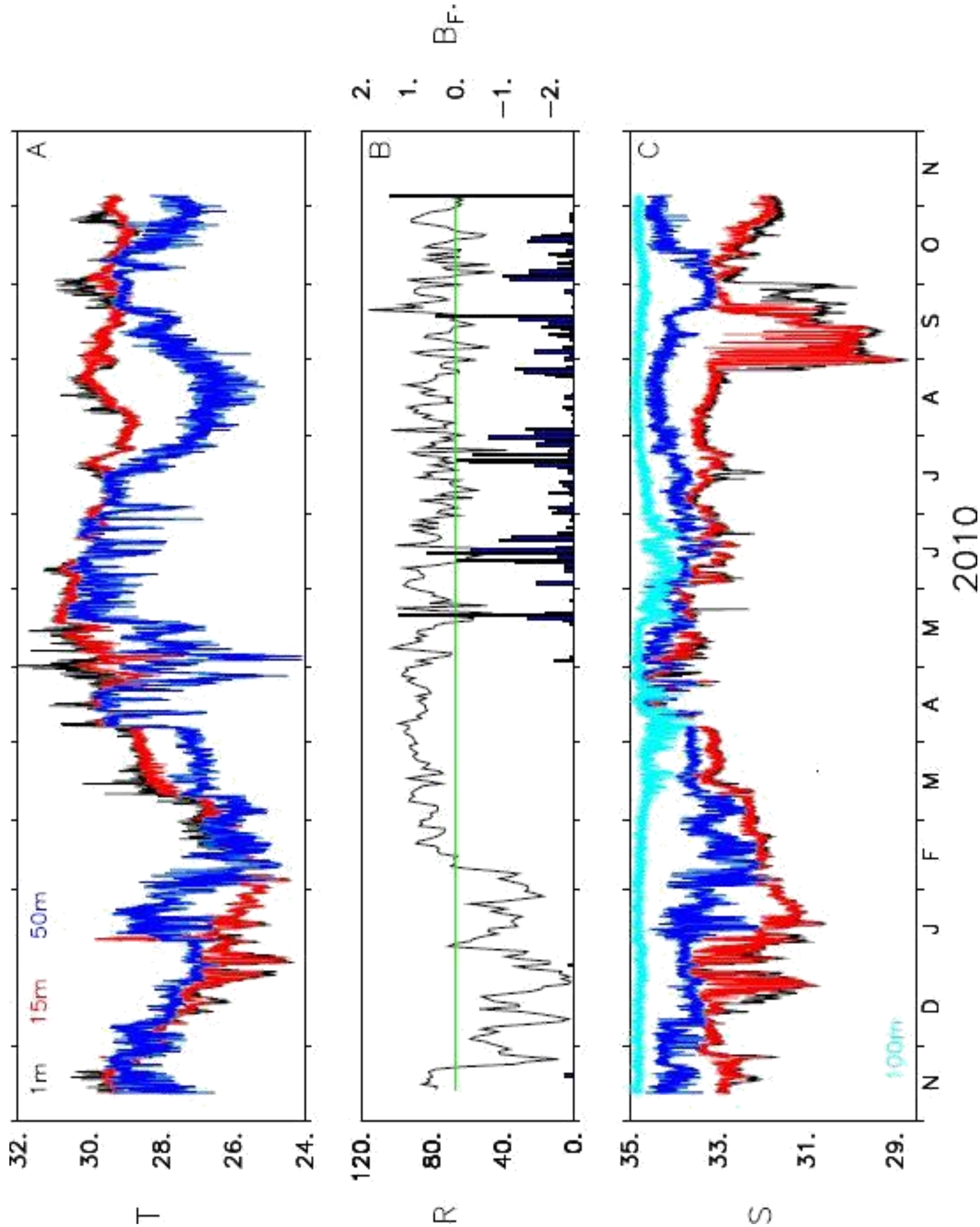


Fig. 57: November 2009-November 2010 observations from a mooring at 18°N,89.5°E with 10-minute sampling. **(A)** temperature at 1, 15 and 50 m depth; **(B)** satellite-derived daily rainfall (mm/day) and surface buoyancy flux (kg/m^2 per day; right axis) at the mooring location; **(C)** salinity at 1, 15, 50 and 100 m depth.

The sharp fall in SSS (4 g/kg in a few days) at the end of August is not due to rain (**Fig. 57 C**); based on the moored current record (**Fig. 58**) and geostrophic currents from satellite sea surface height, we attribute the SSS drop to river water as the summer river plume arrives at the mooring (Sengupta 2001a, Vinayachandran 2002). The low SSS in winter (it does not rain in the Bay at this time) is due to river runoff and rain in the 2009 summer monsoon season. Trajectories based on satellite-derived currents suggest that the river water travels south with the EICC in October-November, turns offshore and returns to the north Bay.

The episodes of temperature inversion in winter 2009/2010 (**Fig. 57 A**) are also related to episodes of low surface salinity (**Fig. 57 C).** As the river water moves over warm subsurface water, the shallow, fresh layer cools in response to net surface heat loss. Penetrative sunlight beneath the shallow halocline (or mixed layer) likely contributes to warming the subsurface water (Sengupta 2001a). Near-surface inversions also occur in summer (see below).

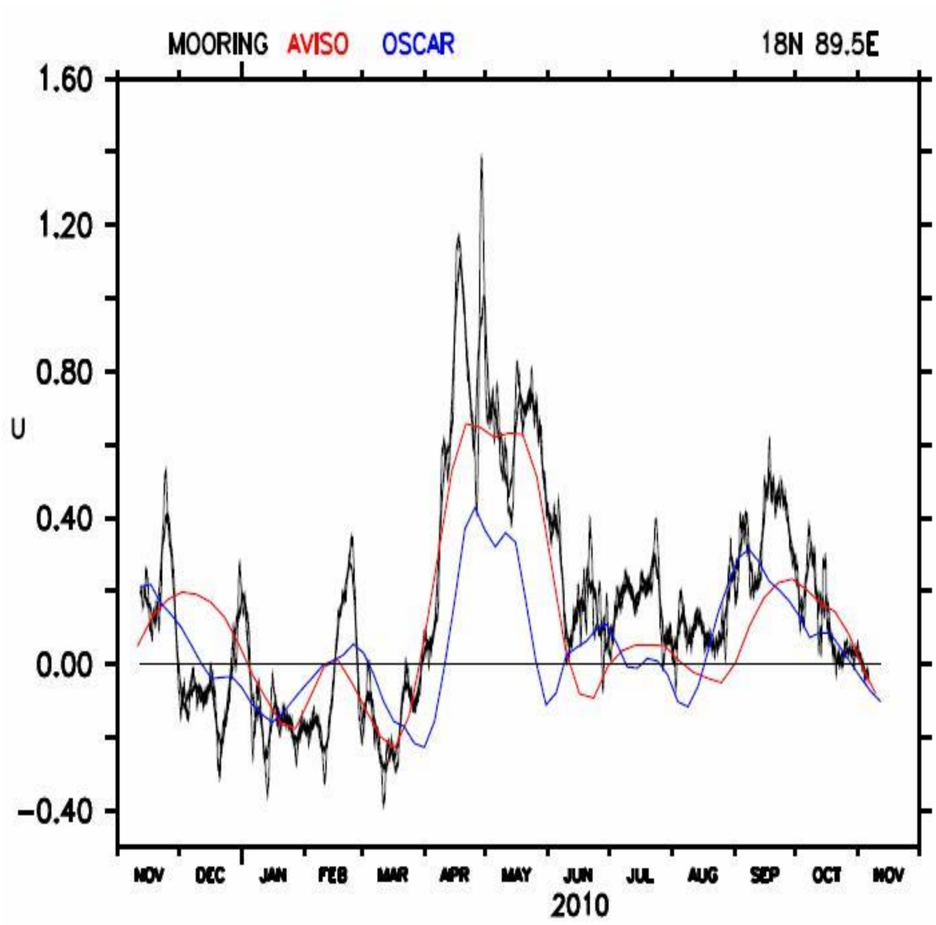
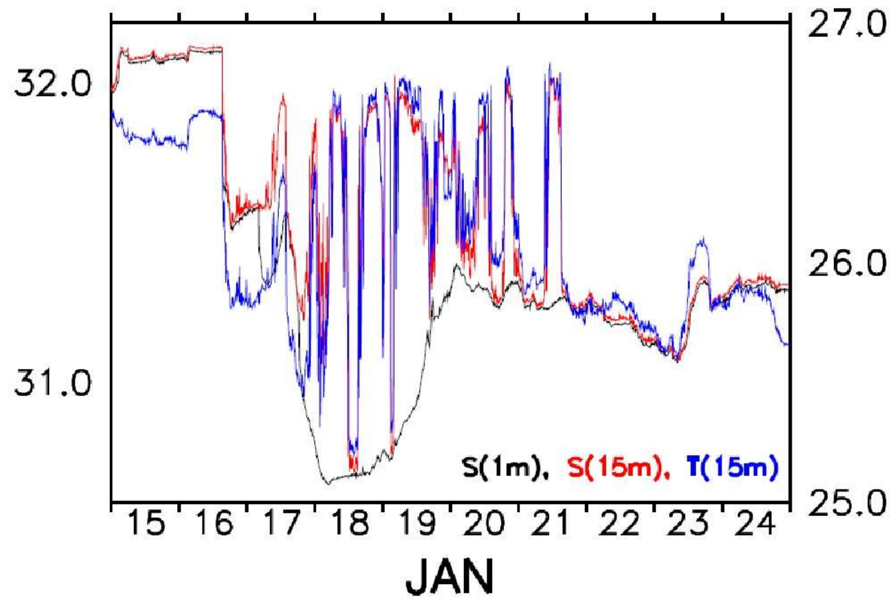


Fig. 58: Zonal current (m/s) at 5 m depth from the 18°N mooring, and satellite derived AVISO weekly geostrophic current (red), and OSCAR 5-day geostrophic plus Ekman current (blue). Daily (grey) and 5-day (black) mooring currents are shown to remove high-frequency fluctuations.

Surface salinity increases from January -April, when the Bay is spanned by an anticyclonic gyre (McCreary 1993). The deep layer of warm, salty water in April arrives in the offshore jet at 18°N associated with the spring western boundary current. Surface salinity gradually falls by about 1 g/kg through the monsoon season. Near-surface density stratification is dominated by vertical salinity gradients at most times. Throughout summer and autumn, potential density at 7 m depth exceeds that at 1 m by over 0.05 kg/m^3; by this definition the mixed layer depth would be shallower than 7 m in summer and autumn, and shallower than 15 m over the entire record. The mean Brunt-Vaisala period (the shortest internal wave period) over the record is about 100 seconds.



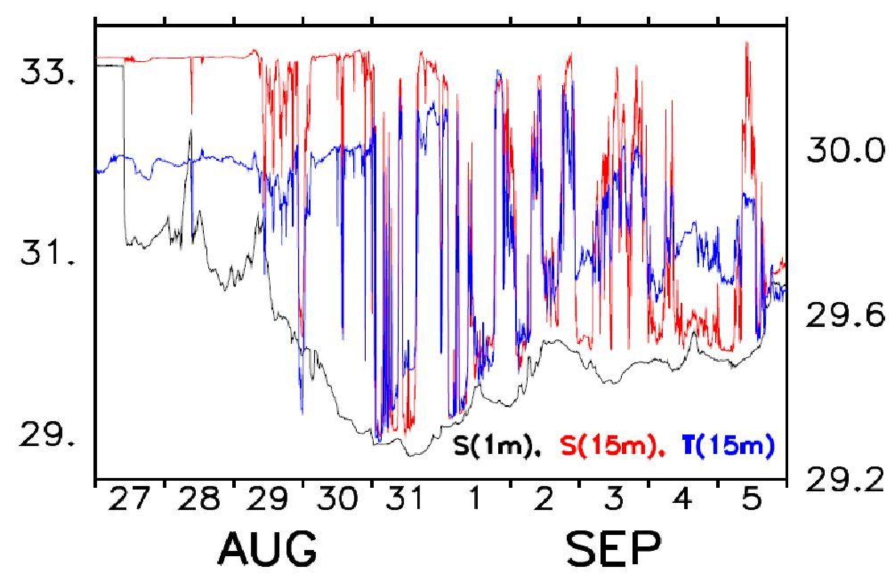


Fig. 59: 10-minute 1m salinity (black); and salinity (red) and temperature (blue) at 15 m depth, in January (top) and August-September (bottom) of 2010.

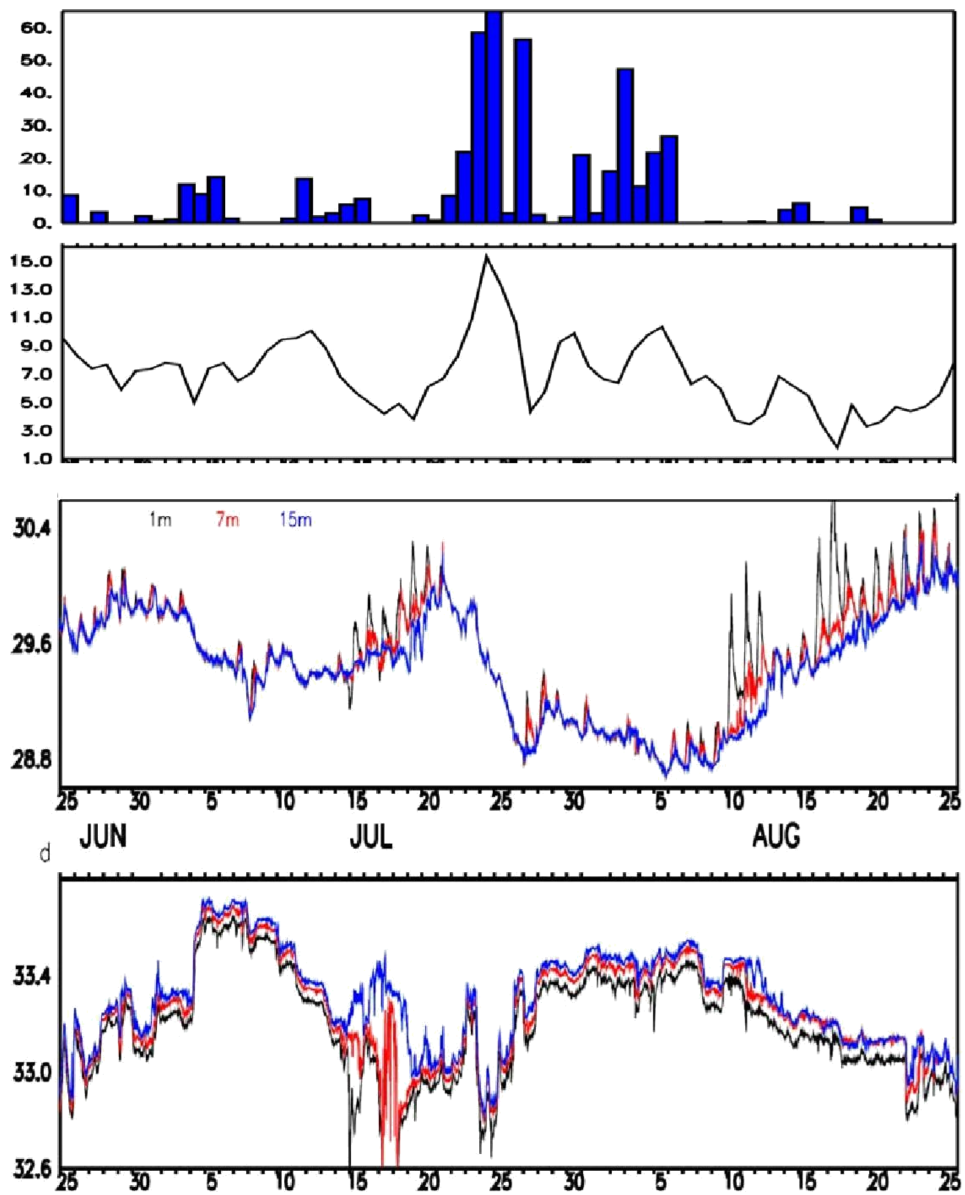


Fig. 60: 10-minute S (bottom panel) and T (second from bottom) at 1, 7, 15 m depth from the 18oN mooring during the 2010 summer monsoon. Satellite-derived daily rainfall (mm/day; top) and windspeed (m/s; second from top) are also shown.

During both summer and winter episodes of fresh surface water ("river" water) at the mooring, the fluctuations of 15 m T and S at 15 m depth are in perfect synchrony. These coherent fluctuations can have periods as short as 20-30 minutes (note the inverse Nyquist frequency for 10 -minute sampling is 20 minutes), but semidiurnal and quasi-daily periods dominate (**Fig. 59**). The 15 m sensor shows a "flip-flop" between cool river water and warmer seawater; the temperature of subsurface seawater is about 30°C in summer and 27°C in winter. Note that a shallow fresh layer and a deep warm layer is common through the summer monsoon season, but inversions are rare (see **Fig. 57**).

Coherent fluctuations of T and S in the presence of sharp vertical salinity gradients are also found at 7 m, and occasionally at other depths. We interpret the fluctuations as internal waves on a shallow halocline: The boundary between river water and seawater is sharp, but not smooth. In other words, the interface is corrugated, likely by internal waves; although the period of the disturbances are evident, we cannot estimate their amplitude from these observations.

As a shallow pool of river water moves past the 15 m sensor, it alternately samples river water and seawater. The sharpness of the winter halocline is remarkable, because the river water has travelled at least 5000 km over 5-6 months (if our surmise about its path is correct) . See Shetye (1996) and Sengupta (2006) for observational evidence of river water maintaining its identity over large distances, implying little mixing with ambient seawater.

As mentioned earlier, SST cools in response to net surface heat loss in the wet (active) phase of the summer monsoon, and warms in the dry (break) phase when the ocean gains heat at the surface. The upper 15 m of the north Bay cools about 1 ^{o}C in five days in July 2010 in rainy, windy conditions, and warms 1^{o}C in 15 days in August under clear skies and weak winds; daytime SST is 0.5-1^{o}C warmer than at night in this period (**Fig. 60**). Salinity, however, has vertical gradients exceeding 0.1 g/kg across 1 m and 15 m depths (equivalent to a density gradient of about 0.075 kg/m^3) through July and August. Note the coherent evolution of salinity at 1, 7 and 15 m depth, with flat periods and abrupt jumps (“shocks”). The range of jumps is 0.05-0.6 g/kg, with typical size of 0.1 g/kg (the nominal accuracy of the salinity sensors is 0.01 g/kg). From the observed 5 m current speed, we estimate the size of three prominent features with significant jumps on either side to be 30, 70 and 100 km; the distances across individual large shocks are 8 km (4 July), 20 km (23-24 July) and 1.5 km (22 August).

Thus we have a new view of the near-surface north Bay during the summer monsoon: It is dominated by mesoscale fresh pools (or filaments) and sub -mesoscale salinity fronts (Tandon 1995, D'Asaro 2011). There is no classical mixed layer – the ocean is stratified by salinity and density at the surface, irrespective of wind speed. The mechanisms that sustain a barrier layer (Cronin 2002) through summer need to be understood. Note that surface buoyancy flux is positive even in the active phase of the monsoon, because rainfall exeeds evaporation, and the effect of freshwater on buoyancy dominates the effect of heat flux (**Fig. 57 B;** see **Fig. 49**).

The 18^{o}N observations raise an important question about vertical mixing in the Bay of Bengal. Relatively fresh water with salinity lower than 34 g/kg is present at 50 m depth during Decmber 2009 to March 2010, June 2010 and September-October 2010, in spite of very stable near-surface density gradients (**Fig. 57 C**).

Low-salinity water can reach subsurface depths either by large-scale downwelling or diapycnal mixing. Gridded Argo data and satellite sea surface height suggest that the occurence of fresh, warm water at 50 m in September-October 2010 is associated with an anticyclonic (downwelling) eddy.

The presence of fresh water at 50 m in December-January and February-early April is somewhat harder to interpret, because negative wind stress curl can lead to basin-wide downwelling in the central Bay at this time. However, the abrupt appearance of cool, low-salinity water at 50 m in early December 2009 suggests that vertical mixing has occured at some point along the trajectory (as the water moves toward the mooring). Surface-forced mixing due to negative buoyancy flux is possible in winter; the local surface buoyancy flux at the mooring is negative from late November 2009 to mid-February 2010.

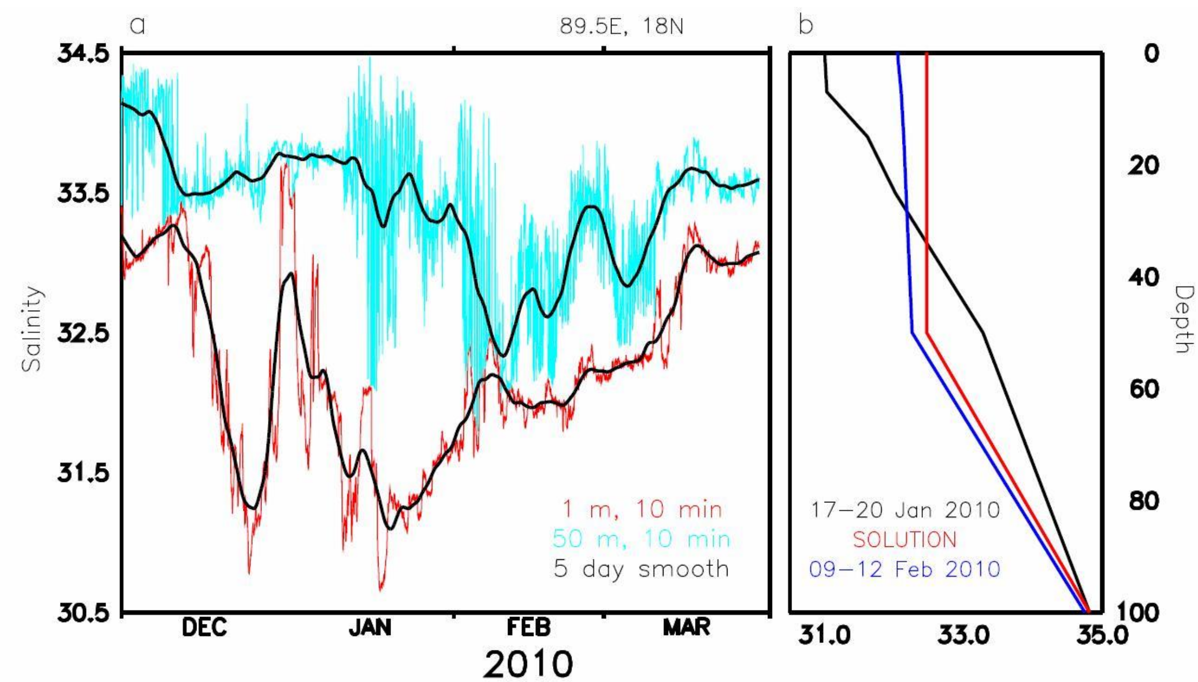


Fig. 61: (a) 10-minute Salinity (g/kg) at 1m (red) and 50 m (blue) depth , 5-day running mean salinity (black) overlaid; (b) observed salinity profiles on 17-20 January (black; "initial") and 9-12 February 2010 (blue), and the predicted salinity profile (red) that would result from mixing the initial profile to 50 m depth. In our calculation, salt, heat and mass in the upper 100 m are conserved.

The observations indicate active vertical mixing from 25 January to 10 February (see **Fig. 57**). The increase of near-surface salinity and decrease of subsurface salinity approximately conserves salt in the upper 100 m (**Fig. 61**). Subsurface temperature decreases by nearly 3 ^{o}C during this event due to mixing with near-surface cool water; surface temperature, however, continues to cool in response to negative net heat flux. Total surface buoyancy loss during the mixing event is comparable to (but smaller than) the observed change of density in the upper ocean.

If cool, fresh water lies on top of warmer, saltier water, i.e. salinity and temperature both increase with depth, double-diffusive mixing is possible due to the difference in the molecular diffusivity of salt and heat. A layering instability (Ruddick 2003) can arise depending on the ratio $R_\rho = \alpha\theta_z/\beta S_z$, the relative contribution of temperature and salinity to the density gradient. Potential energy in the (unstable) temperature stratification drives convective motion in layers separated by sheets with large vertical gradients (**Fig. 62**); the heat flux is upwards, and salinity and density fluxes are downwards. In the moored observations (total samples about 51700), necessary conditions for diffusive convection are satisfied 42% of the time between 1 m and 7 m depth, and 33% of the time between 7 m and 15 m, mostly in winter when temperature inversion is common (**Fig. 63**). Interesting dynamical effects are also possible in such a setting (Krishnamurti 2011). Double -diffusive processes may be gentle, but their effects on near-surface stratification need to be considered alongside "normal" turbulence (Inoue 2007).

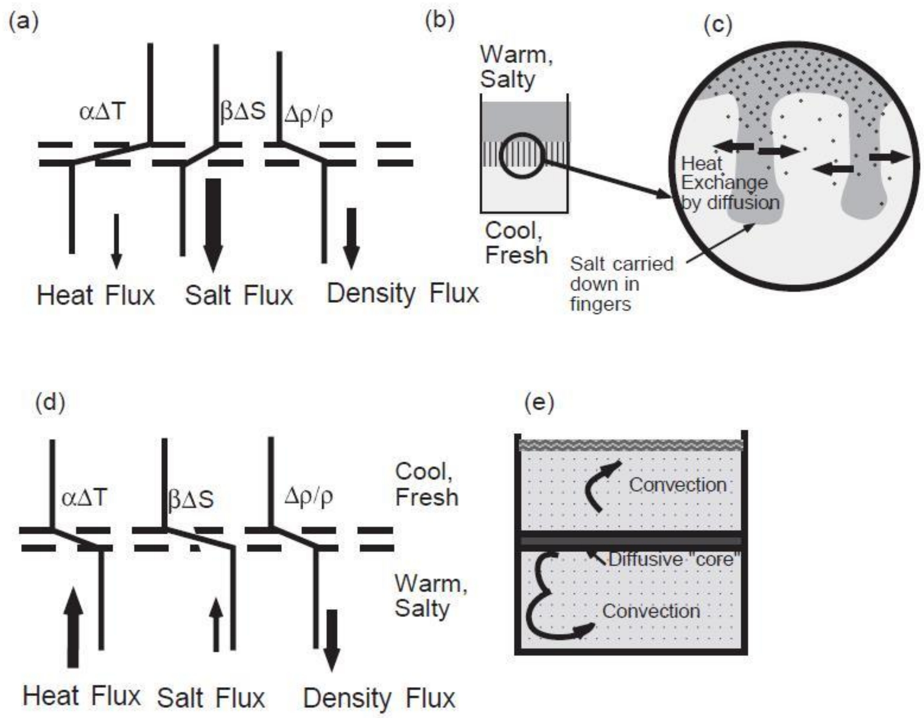


Fig. 62: Schematic of double-diffusion (a, b, c) salt fingering in the presence of warm, salty over cool, fresh water; (d, e) when cool, fresh water lies above warm, salty water, layering instability leads to convective layers and diffusive interfaces (sheets). From Ruddick 2003.

Several other mechanisms of diapycnal mixing are likely to be important in the Bay of Bengal. Tidal amplitudes are high in the northern Bay, and tidal mixing on the broad continental shelf in the north could well influence upper ocean salinity and temperature not only on the shelf, but also in the open ocean. Large tidal fronts, such as the one in the Andaman Sea (Ramaswamy 2004), are probably important in both dynamics and near-surface thermodynamics (suspended sediments and water clarity). The effects of river runoff and tides on stratification have been studied in individual estuaries (e.g. Acharyya 2012), but basin-scale effects on Bay of Bengal SST and atmospheric convection (see Godfrey 2000, Jochum 2008 and Koch-Larrouy 2010 for examples from the Indonesian seas) remain to be explored.

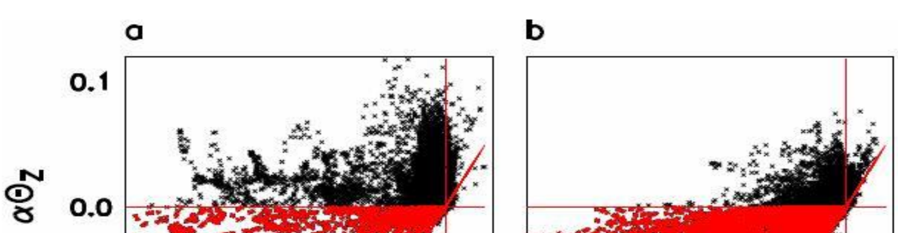


Fig. 63: Turner angle from the 18^{o}N observations: Coefficient of haline contraction times salinity gradient, versus thermal expansion coefficient times potential temperature gradient, between (a) 1 m and 7 m depth, and (b) 7 m and 15 m. The red dots represent all data points at which the necessary condition for diffusive convection is satisfied.

When tides encounter seabed topography, they generate internal waves. There are several reports of internal waves and large-amplitude solitons in the Bay of Bengal and Andaman Sea (see Rao 2010 and references), but systematic in situ observations of internal waves are lacking. The influence of internal waves of tidal, intertial and other periods on upper ocean mixing (Muller 2000) needs to be estimated in this basin.

Energetic mesoscale eddies (10-100 km; the Rossby radius is ~50-150 km in the Bay) are a part of quasi two-dimensional geostrophic turbulence; they transfer energy mainly to larger scales (Ferrari 2008). Recent advances in observing techniques and modelling permit study of an important scale of motion called the sub-mesoscale (order 1 km; Thomas 2008). The upper ocean is rich in kilometre-scale structures, often seen in high-resolution satellite sea surface temperature(e.g Flament 1985) or chlorophyll maps (see references Mahadevan 2002). Sub-mesoscale flows arise from forced or unforced instability, have Rossby number of order 1, and are intermediate between the mesoscale and three-dimensional motions at small scale where energy is dissipated.

Towed CTD sensors are used to capture sub-mesoscale structures in the upper ocean associated with fronts (e.g. Rudnick 1999; D'Asaro 2011) . The vertical velocities associated with sub-mesoscale structures can be much larger (order 100 m per day) than at mesoscales (Mahadevan 2006); they promote transfer of mass and tracers between the surface boundary layer and the interior. Buoyancy fluxes are enhanced by sub-mesoscale processes, rapidly changing mixed-layer properties; for example, measurements with Lagrangian mixed-layer floats show changes in near-surface stratification within a day that are not due to surface heat fluxes (Lee 2006). Imagine that the upper ocean has large lateral gradients (a “front”), but is vertically well-mixed. Baroclinic instability of the mixed-layer front can give rise to sub-mesoscale eddies that lead to rapid slumping of isopycnals and stratification of the upper ocean (Bocaletti 2007). Experiments with a high resolution non-hydrostatic model show that sub-mesoscale eddies generated by instability of the front restratifies the mixed layer in days (Mahadevan 2010).

We have mentioned the possibility of sub-mesoscale signals in the 18 °N observations, but no surveys were carried out of spatial variabilty in the vicinity of the mooring. Promising sites for detailed measurements are in the vicinity of the summer river plume (Prof. Hidekatsu Yamazaki, personal communication), the eastward offshore jet in spring, and near the irregular topography of the Andaman ridge (e.g. Kunze 1993). Many regions of the Bay of Bengal as well as many important questions of small-scale physics await exploration. We end with a quote from Thomas 2008: "Present-day global circulation models do not resolve submesocales; conceivably, this is the reason for the dearth of restratifying processes and mixed layers that are far too deep in the models ..... Hence, parameterizing these processes is of interest to climate modeling."

9.2 Atmospheric studies : Estimation/measurements of Cloud properties relevant to model parameterization under CAIPEEX program of IITM

9.2.1 Science Objectives

In aerosol studies, there is a large number of nonlinearly coupled sub-processes which need to be considered in the model for realistic representation of cloud-aerosol interaction. Therefore the gain in information is often largely improved by supplementing the experiments with numerical simulations employing detailed physical and chemical process in the models. Thus, the objective of science plan is to evaluate/validate the response of microphysical processes in CGCM e. g. CFSV2 where cloud water and cloud ice are calculated prognostically. Quantitative forecasting of precipitation has been one of the major challenges in operational General Circulation Model (GCM). Model's quantitative precipitation forecasts can be improved by realistic representation of microphysical processes. The effects of clouds on the treatment of condensation and evaporation are also important in the precipitation calculation. It is already seen that simple schemes are able to produce some reasonable precipitation forecasts however, one cannot neglect cloud water and cloud ice in the model thermodynamic and hydrological fields. Furthermore, the exclusion of ice-phase clouds in the model can lead to under estimation of latent heating and therefore significantly influences the feedback to dynamical fields.

Thus some in-situ studies are important:

* Estimation/measurements of ice water content (IWC) during ISM. During previous CAIPEEX campaign there was no measurement of IWC. Thus in forthcoming CAIPEEX experiment we propose for the measurement of IWC. Measurements of IWC can be obtained from the PMS two-dimensional cloud and precipitation (2D-C and 2D-P, respectively) probes (Knollenberg 1981) following the procedure of Fleishauer et al. (2002), which utilizes the ice mass–dimensional relationship of Mitchell et al. (1990). The IWC measurements presented here have an estimated error of less than 50% (Carey et al. 2008) (details are in Noh et al. 2013, JAMC).

* Cloud ice particle size and number concentration also be measured along with cloud drop (liquid) size and number.

* Measurement of relative humidity (RH) profile in different cloud condition (clear, cloudy and rainy) during ISM.

* Aerosol number concentrations should be measured from nucleation mode to coarse mode. The chemical composition of the aerosol particles may also be addressed.

* Freezing of droplets: aerosol effects on the cloud ice phase.

* Effect of particle structure, composition and mixing state (internal/external mixing).

9.2.2 Cloud modeling application:

The ice cloud estimates in current global models exhibit significant inconsistency, resulting in a significant amount of uncertainties in forecasting/simulation. Vertically resolved ice water content **(IWC)** is important for evaluating the global models. To account for the varied nature of the model parameterization schemes, it is valuable to develop methods to distinguish the cloud versus precipitating ice components.

In-situ (CAIPEEX) total IWC can be divided into small and large ice hydrometeors, using the ice particle size distribution (PSD) parameters (*Chen et al. 2011*). This information will be important to understand the mixed-phase (snow and graupel) processes over Indian subcontinent during ISM. This estimation can be applied to evaluate the IWC estimates from our current CFSv2 model which is one of the objectives of "Monsoon Mission".

The similar strategy is adopted by the European Centre for Medium-Range Weather Forecasts model and the finite-volume multi-scale modeling framework model (GSFC, NASA), pointing to specific areas of potential model improvements.

At IITM numerous experiments on the nucleation efficiency of mineral dusts, soot, bio-aerosols, and coated particles can be conducted in future. Based on these experimental results, parameterizations will be developed for models on different scales in order to enhance our understanding of aerosol effects on the cloud in general and ice phase in particular. The goal of these efforts is to gain insight regarding the aerosol influence on the development and intensity of precipitation and to reduce the uncertainty of the aerosol indirect effect on cold and mixed phase clouds in regional and global models.

* Parameterization development for cloud resolving model and General Circulation model (GCM).

* Different type aerosols (CCN, or IN) and giant cloud condensation nuclei (GCCN): Importance for the hydrological cycle and climate on the regional and global scale

* Anthropogenic aerosol effects via mixed phase and ice clouds

Chapter 10: Implementation Plan / Strategy

10.1 Short and Medium Range Prediction (IMD and NCMRWF)

All current operational NWP systems/models have limitations in predicting anomalous monsoon features, particularly the extreme events like heavy rainfall. In view of limited skilled manpower resources available in the country, a view is emerging that to begin with the best possible model, from among those that are available, should be chosen. Then concerted efforts in a synergetic fashion should be put to further improve its performance over Indian monsoon region. The following is proposed as guideline for it:

- present performance
- better technology(e.g. 4D-VAR; Land Surface Assimilation etc.)
- active involvement of large number of interested groups in system development

- collaboration in areas of mutual interest
- better documentation
- software design/technology permitting large, diverse groups to work in parallel

The experience at NCMRWF shows that unified model of UKMO is most suitable. It captures monsoon synoptic features well. Over monsoon region, its performance over short and medium range is consistently better than the system presently operational at NCMRWF and also that of NCEP, JMA etc. It uses 4-D VAR assimilation system which extracts more information from observations consistently, in a better way. A large number of centres (Australia, New Zealand, South Korea, South Africa, Norway) have started using this system.

The roadmap for improving the monsoon prediction is given below:

- To implement the Unified Model (UM) at 25 km and its associated components that forms an end-to-end NWP system at NCMRWF. The implementation programme will last through 2010-11. It is envisaged that the UM will become the operational weather prediction model if its forecasts are found to be better than that of the current operational model. The resolution will be subsequently increased to 15 km.
- To implement regional version of UM at 12 km resolution over Indian monsoon region for high impact weather and further downscale for nowcasting.
- Implement 4-D VAR system of UKMO develop capability for assimilating data/radiances from upcoming Indian satellites and Doppler Radars.
- Implement high resolution Ensemble Prediction System (EPS) based on UM.
- Implementation of UKMO coupled atmosphere ocean coupled modeling system. (To increase temporal range of forecast from one to two weeks, inclusion of atmosphere-ocean interaction is essential).

In addition to IMD efforts on GFS model improvements, it is proposed that IITM will also test their model development activities both in CFS and GFS to test how error growth after implementation of new physics/parameterization schemes in the model improved at short and medium range predictions.

10.2 Seasonal and Extended Range Prediction (IITM)

Climate Forecasting System (CFS) model developed by National Center for Environmental Prediction (NCEP) of USA is reasonably better compared to other coupled models in predicting the monsoon rainfall on seasonal and extended range time scales. This model is already available to Indian Institute of Tropical Meteorology (IITM, Pune) and successfully running on their high performance computer. Prediction skill of this model at normal resolution of AGCM is above 0.4 and hence, it is proposed to use this model for further development to improve the prediction skill of Indian summer monsoon rainfall. All groups that get involved in this mission will use this model (or components of this model) for development and research activities, so that concerted efforts of different groups will result in a better tool for monsoon prediction.

For improving the prediction skill of the monsoon rainfall in dynamical models, it is important to improve the systematic bias of the models. At a fundamental level, models have systematic biases (errors) in three areas, viz., (i) in simulating the space-time spectra of tropical clouds, especially during northern summer. This problem can be largely identified as inability to simulate the summer monsoon intra-seasonal oscillation (MISO), (ii) most models have serious bias in simulating the observed proportion of convective and stratiform precipitation (net heating profile: proportion of stratiform to convective clouds), (iii) the phase of diurnal cycle. These three aspects can be achieved by the following means:

- It is believed by many researchers that increasing resolution of the models it is possible to simulate the space-time spectra of tropical clouds and possibly increase the prediction skill of the models. Some even go to the extent that global cloud resolving models may be required (Shukla et al. 2009). This is certainly a direction to be explored. To a certain extent increasing resolution of the coupled model will enhance the prediction skill of the model, however, beyond some point it is unlikely that the prediction skill will be further improved. For example, the 20-km global model of MRI still fails to simulate the MJO correctly (Rajendran et al. 2008).

    - In recent times, a new concept "Super Parameterization" is evolving in which a coarse resolution AGCM is coupled with a cloud system resolving model. In this model resolution. In general, a GCM that uses super parameterization is three times more CPU intensive than an AGCM that uses conventional parameterization schemes. It appears to be one of the promising areas of research to improve seasonal monsoon prediction.
    - Many of the conventional parameterization schemes are developed by other nations, based on the knowledge acquired by intensive observational programs carried out in those regions. It is not yet understood, whether same parameterization schemes are applicable over Indian monsoon region. Observational campaigns are already started by MoES/IITM to address this issue. Similar observational campaigns are also required to enhance the understanding of land surface processes and ocean mixing parameterization schemes.

    - Recent studies have shown that assimilation of subsurface ocean data and using the assimilated data in a coupled general circulation model significantly enhance the prediction skill of weather. Research in similar direction in land surface data assimilation is very much essential to improve the prediction skill of the monsoon rainfall.

It is proposed to encourage research efforts by national and international research groups in the above mentioned areas of interest. Support could be rendered to the International community through funding on case basis and to support observational programs that will result in better understanding of the processes that will in turn result in improving the parameterization schemes in AGCMs, OGCMs, and land surface models.

In each of the areas, following important aspects will be addressed:

- Dynamics of Inter Annual Variability (IAV) of Monsoon.
- Responsible factors that make each year monsoon different.
- The combination of driving forces that makes each monsoon different.
- Basic understanding of tropical clouds, its parameterization and representation of diurnal cycle.
- Realistic representation of various scale interactions at various time scales.

Mission activities related to Short & Medium Range and Seasonal & Extended Range Prediction, at IMD

State of the art atmospheric model **(T574L64)** with latest assimilation modules has been implemented at IMD Delhi for enhancing its short to medium range weather forecasting capability. The new model has a horizontal resolution of approximately 25 km. This high resolution Global model with advanced assimilation modules is also helpful for providing initial and boundary conditions for high resolution meso-scale models (like the WRF model) to be run at IMD HQs and other centres.

For the improvement of the monsoon prediction in the short and medium range time scale, assimilation of the data from satellites (INSAT-3D Radiance), wind profilers, GPS sonde, meso-network (Automatic Weather Stations), buoys, aircrafts etc. in the real time mode will be very crucial. Thus, IMD will also implement the latest assimilation modules of GFS and high resolution WRF. This will help in prediction of meso-scale heavy rainfall events associated with monsoon system.

During recent years, Ensemble Prediction System (EPS) has emerged as a powerful tool for improving medium range weather forecasts. In the EPS, single model is used with multiple sets of initial conditions to obtain the final forecast. While Singular Vector and Bred Vector (BV) methods are still widely used in generating initial perturbations, Ensemble Transform of BV, Ensemble Transform Kalman Filter and Ensemble Data Assimilation are also implemented in various centres. IMD should implement EPS. This would allow IMD to get access to EPS outputs of other global centres and provide an opportunity for development and implementation of a Probabilistic Forecast System (PFS) using EPS outputs of all available centres for better forecasting of monsoon rainfall in short to extended range time scale.

IMD will also verify the performance of model forecast variables in the short and medium range time-scales.

All current operational NWP systems/models have limitations in predicting anomalous monsoon features, particularly the extreme events like heavy rainfall. In view of limited skilled manpower resources available in the country, a view is emerging that to begin with the best possible model, from among those that are available, should be chosen. Then concerted efforts in a synergetic fashion should be put to further improve its performance over Indian monsoon region.

The following is proposed as guideline for it:

- Present performance
- Better technology (e.g. 4D-VAR; Land Surface Assimilation etc.)
- Active involvement of large number of interested groups in system development
- Collaboration in areas of mutual interest
- Better documentation
- Software design/technology permitting large, diverse groups to work in parallel

10.3 Seasonal and Extended Range Prediction

- As the seasonal and extended range forecast of monsoon rainfall requires a good coupled model, IMD will implement the latest version (Version 2.0) of the operational coupled model of NCEP, known as the Climate Forecast System (CFS) with complete assimilation modules (both atmosphere and ocean) at IMD Delhi. Since the atmospheric version of the CFS is already operational in the HPCS system at IMD New Delhi the implementation of the CFS at IMD Delhi will be very useful.

- After the implementation of the NCEP CFS at IMD New Delhi, it will like to generate the real time deterministic and probabilistic extended range forecasts (beyond 7 days to one month) on smaller spatial scale (meteorological subdivision scales) by using the NCEP CFS model to be implemented at IMD Delhi along with other coupled model forecasts from other centres.

- IMD Delhi and IMD Pune offices will conduct diagnostics of the CFS simulations for the extended range and seasonal forecast, respectively, to prepare the verification statistics of model outputs as per standard verification procedure. The feed back from these analyses will be provided to IITM for further improvement of the model. Based on these analyses IMD will also like to develop dynamical-empirical model for the improved forecast of monsoon in the extended range to seasonal scale.

- Initially IMD, Pune will use the HPCS of the IITM, remotely for the seasonal forecast. Under the National Monsoon Mission, IMD Pune will collaborate with IITM in developing the dynamical seasonal forecasting system based on NCEP CFS and subsequently implement it at its office.

- Subsequently, depending on the availability of the computing power of the HPCS at IMD, Pune the CFS coupled model will be ported to IMD Pune for the operational seasonal forecast.

- In addition to the above, IMD Delhi office will work on implementation of an operational extended forecasting system based on empirical model (like the SOM model of IITM) in collaboration with IITM.

- IMD Pune will work on updating daily grid point rainfall data at two different high resolution spatial grids (1^ox1^o and 0.5^ox0.5^oetc.) for participating institutions, which will be helpful for model verification.

10.4 Proposed modalities to achieve mission objectives

10.4.1 Seasonal and Extended Range Prediction (IITM/IMD)

A state of the art dynamical prediction system for seasonal mean and extended range prediction of active-break spells is not operational in the country. With active collaboration of IMD and IITM it is planed to set up such a system, evaluate its hind-cast skill and use it by the IMD for the operational forecasting. IITM plans to put in place a strong R&D plan to continuously improve the skill of these forecasts. The academic community in the country has made great advances in understanding variability and predictability of the monsoon. So far, this knowledge has not been translated to improvement of operational forecasts. IITM will coordinate the effort. Following modalities are proposed:
The monsoon mission program will be initiated at IITM by deploying/employing the following personnel

- Scientist F/G to oversee all the matters of the mission and to act as program manager of this mission

- Two Scientists C/D for assisting the program manager to identify various issues related to national monsoon mission and organize the meetings/ workshops to enhance the interaction among participating R &D and academic institutes.

- Two Computer Engineers in the cadre of Scientist D/E to assist in porting/coding various dynamical models and to help other partners.

- One UDC to assist in administrative procedures.

- An announcement of a Research Opportunity will be made through which proposals will be invited from National and international Institutes on very specific projects through which improvement of the CFS model could be achieved towards better forecast of monsoon.

- Proposals will be formulated so that they are directly relevant in improving the forecast of the CFS model system.

- Certain amount of funding for the National Partners as well as the International Partners will be year marked.

- The Proposal partners will be allowed to use the High Power Computing (HPC) facility available at IITM which will be suitably enhanced for this purpose.

- Funding for students, post docs and some scientists time (consultancy) and some minor equipments may be provided.

10.4.2 Short and Medium Range Prediction (NCMRWF)

To accomplish the mission objectives NCMRWF will require 20 permanent scientists for the following areas of work:

Areas of Work	**Posts**	**Bifurcation of Posts**
Data Processing & Quality Control	02	Sc. D(1), Sc. B(1)
Global & Regional Atmospheric Data Assimilation	03	Sc. D(1), Sc. C(1), Sc. B(1)
Model Dynamics & Physics	04	Sc. E(1), Sc. C(1), Sc. B(2)
Ensemble/Multi-model Ensemble Prediction	03	Sc. D(1), Sc. C(1), Sc. B(1)
Model Diagnostics	03	Sc. D(1), Sc. C(1), Sc. B(1)

Ocean Modeling and Data Assimilation for Coupled Modelling	03	Sc. E(1), Sc. C(1), Sc. B(1)
Computer Software Specialists	02	Sc. C(1), Sc. B(1)
Total	**20**	

10.5 Need for Enhanced Computing Infrastructure

In recent years there has been a dramatic enhancement of computing power in the new generation machines. MoES has acquired 3 state of the art High Performance Computing machines to conduct its operational and research activities. IMD has received a 15 Teraflop machine for its operational Numerical Weather Prediction (NWP) activities to run the global and regional forecast models for Short to Medium Range Forecasts. IITM has received a 70 T flops machine for its research and model development works (Please see Annexure B; for further details).

Concurrently, the International community has been active in collecting data from atmosphere over land and ocean areas (from the ocean depths and surfaces too) by deploying buoys, floats and specialized diving sensors called Argo etc. The land surface processes controlling surface flux of water vapour and energy are also being monitored. Along with this the data available from the ongoing Modernization Program of the IMD will help in improving performance of Coupled Models for seasonal and climate forecasting by providing input for data assimilation systems. Coupled forecast systems require initial conditions for Land, Atmosphere and Oceans, and those initial conditions can be obtained by running data assimilation systems of respective components. Data assimilation techniques need lot of computer resources as the initial condition for coupled models will be generated iteratively from observations and model guess fields. Since all prediction models are sensitive to initial conditions several tens of experiments (with the same model) have to be carried out to issue an operational/experimental forecast to reduce errors in the forecasted field.

To meet these demands, it is proposed to undertake this task by adding infrastructure beyond its medium range needs. Machines of Peta flop range and large volume data handling systems will be required along with necessary human resource development and capacity building, which would be taken care by the **'Program for Advanced Training in Earth System Science and Climate'** of the MoES being started under the leadership of the IITM at Pune.

10.6 Short and Medium Range (NCMRWF/IMD)

NCMRWF will coordinate the effort on short and medium range prediction system. Specific scientific problems will be identified and opportunities will be announced to invite well defined projects with specific deliverables contributing to improvement in the forecast accuracy and range. Separate funding will be earmarked in NCMRWF budget for supporting this effort and for collaborative research. NCMRWF will also make available enough computing power to all collaborating partners. Adequate funding for this purpose will be earmarked.

At present, NCMRWF has 24 T Flops HPC machine. To meet the objectives of the monsoon mission for medium range prediction there is an immediate requirement to upgrade the HPC to > 250 T Flops.

Both the models from IITM and NCMRWF will be transferred to IMD for making operational/experimental forecasts, and verifying the hindcasts of the model as and when new improvements happen in the model development.

10.7 Approach Strategy, Methodology and Schedule

10.7.1 Seasonal and Extended Range Prediction (IITM)

The approach strategy would take this into account the setting up a framework for generating dynamical forecasts and improvement of the skill of forecasts. The framework for generating dynamical forecasts and improvement of the skill of forecasts would involve importing and porting the model and acquiring the data assimilation system. The more challenging task, however, is the requirement to improve the skill of the forecast of the Indian summer monsoon rainfall that can be achieved through improved parameterization, ingesting more observations (especially satellite observations), improved assimilation techniques, enhanced resolution and improved techniques for land-ocean-atmosphere coupling etc. Continuous assessment of any changes towards the improvement of the skill would be pre-defined.

In order to put such a framework in place and make seasonal forecasts using multi-model ensemble system by 2010 monsoon season it is required to identify a core model. For the mission it has been decided to use the NCEP-CFS model as the core model. However, a plan for improvement of prediction skill of this frame work is critical. Recognizing the fact that such a complex problem needs national effort involving academic and R&D institutes, Ministry of Earth Sciences (MoES) through the "National Mission of Monsoon" will involve all relevant organizations and research institutes for improving the dynamical prediction of seasonal mean monsoon. Following strategy will be followed:

- Focused mission on ‘Seasonal and Intra-seasonal Monsoon Forecast’ to be launched.
- Support focused research by national and international research groups with definitive objectives and deliverables to improve CFS model.
- Support some specific observational programs that will result in improvement of physical processes in climate models.

Probable Partners:

International

- USA: NCEP, COLA, GFDL,IPRC
- Europe: INGV, INPE, MPI
- Asia: JAMSTEC, APCC, CCSR

National Partners

- IISC, IITs, MOES institutes, Universities

Schedule (Time lines)

Action to be taken	Year
• Setting up nodal point at IITM (ii) Set up CFS V 2.0 model at IITM • Identify the strengths and weakness of the model and define the problems for further investigation. Invite the project Proposals and engage the R&D community in improvement of the coupled model	2012-13
• Carryout research on identified problems together with national/ international partners and review the progress made by external experts committee • Implement the experts suggestions in the proposal and carryout the model development activities and test the model’s skill	2012-16
• Expected to have an Indian model, skill of which will be better than the model adopted at the initial stages both for short & medium range prediction and seasonal & extended range prediction	2016-17

• Review the progress made by the national mission (seasonal/extended range prediction)	2016-17

The present proposal wish to evaluate its performance after completing five years and if significant progress is made in these five years then to take the momentum further and to obtain fruitful results, we need to extend the proposal for another five years.

10.7.2 Short and Medium Range Prediction (NCMRWF)

Probable Partners :

International

- Europe: U.K. Met Office, ECMWF
- USA: NCEP
- Asia: KMA, South Korea, CAWCR (Australia)

National Partners

- IISc, IITs, MOES institutes, Universities

Schedule (Time lines)

Action to be taken	Year
(i) Implementation of the UKMO Global 4-D VAR assimilation system and the Unified model (ii) Experimental runs of the UKMO Global 4-D VAR assimilation system and the Unified model, Model inter-comparison studies. Identify the strengths and weakness of the UKMO global modeling system.	2012-13

(iii) Implementation/Diagnosis of the UKMO regional data assimilation system and model (iv) Implementation of the UKMO coupled model	
(i) Identify the strengths and weakness of the UKMO coupled model and define the problems for further investigation. (ii) Implement ocean assimilation system	2013-14
Carryout research on identified problems together with national/ international partners on (i) Data Assimilation, (ii) Model Physics and dynamics, (iii) Diagnostic studies and (iv) Coupled modeling system	2013-16
Expected to have a stable version of complete forecast system, customized for the Indian monsoon.	2016-17

10.8 Evaluation of Monsoon Mission Progress:

Working structure of monsoon mission is shown in Fig. 64. The whole of mission activities will be overseen by Scientific Steering Committee (SSC), which will guide and monitor the monsoon mission activities and suggest future course of action and is the final approval authority of the monsoon mission proposals. The salient results will be reported to an international advisory panel headed by Prof. J. Shukla. Scientific Review and Monitoring Committee (SRMC) reviews the international/national proposals and recommend/defer the proposals. Monsoon Mission Director is the executive authority of the mission activities and major driving force behind the activities of monsoon mission. Project Directors for each sub-mission are identified and they will propose new activities (if any) required to be taken up under monsoon mission which are relevant to their field of responsibility. Project directors are responsible for delivering the mission objectives/deliverables. The Scientific Steering Committee (SSC), the apex body of the Monsoon Mission programme, approves the project proposals, which are recommended by SRMC and finalizes the budget allocation for the proposals.

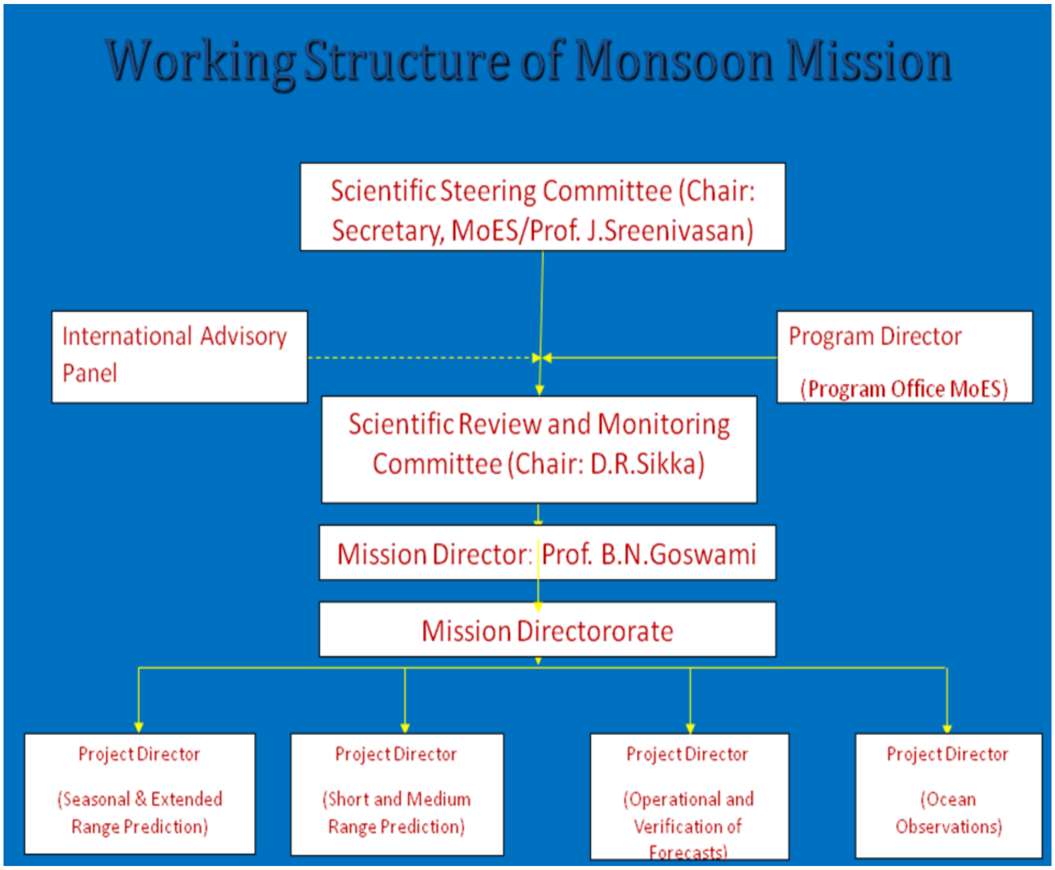


Fig. 64: Working structure of monsoon mission and evaluation process.

Chapter 11: Deliverables

Following major outcome and output are expected from the Scheme:

- Although many centers in the world use dynamical model framework to predict seasonal mean climate routinely, in India such a frame work has to be put in place. Under the National Monsoon Mission concerted efforts by various research and academic institutes in India and abroad are commendable towards developing/improving the current generation of dynamical models to improve the monsoon rainfall prediction, with improved insight of the entire complex phenomena, greater success can be achieved for prediction of monsoon rainfall on different time scales.

- The mission will be focused on improving coupled dynamical models and improvements to current statistical models will benefit from the knowledge gained by the Mission objectives.

- With the data input from a close knit network of Automatic Weather Stations, Automatic Rain gauges and Doppler Weather Radars, the Numerical Weather Prediction models will be benefitted from theses networks as they provide better initial conditions.

11.1 Programme Schedule

11.1.1 Seasonal and Extended Range Prediction

Action to be taken	**2012-13**	**2013-14**	**2014-15**	**2015-16**	**2016-17**
(i) Setting up nodal point at IITM (ii) Set up CFS V 2.0 model at IITM	←→				

Identify the strengths and weakness of the model and define the problems for further investigation. Invite the project Proposals and engage the R & D community in improving the above model					
Carryout research on identified problems together with national/international partners and review the progress made by external experts committee					
Implement the experts suggestions in the proposal and carryout the model development activities and test the model's skill					
Expected to have an Indian model, whose skill will be better than model adopted at the initial stages for seasonal and extended range predictions					
Review the progress made by the national mission (seasonal/extended range prediction)					

11.1.2 Short and Medium Range Prediction

Action to be taken	**2012-13**	**2013-14**	**2014-15**	**2015-16**	**2016-17**
(i) Implementation of the UKMO Global 4-D VAR assimilation system and the Unified model					

(i) Experimental runs of the UKMO Global 4-D VAR assimilation system and the Unified model, Model inter-comparison studies. Identify the strengths and weakness of the UKMO global modeling system (ii) Implementation/Diagnosis of the UKMO regional data assimilation system and model (iii) Implementation of the UKMO coupled model					
(i) Identify the strengths and weakness of the UKMO coupled model and define the problems for further investigation (ii) Implement ocean assimilation system					
Carryout research on identified problems together with national/ international partners on (i) Data Assimilation, (ii) Model Physics and dynamics, (iii) Diagnostic studies and (iv) Coupled modeling system					
Expected to have a stable version of complete forecast system, customized for the Indian monsoon.					

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