# 4
# MULTI-SCALE MODELING PROGRAMME

*This activity is centered around data intensive paradigm where numerics and computing strategies relevant for different scales in a dynamical system are combined to arrive at an effective computational solution than the one obtained from the strategy dealing with the most relevant single scale. The group developed an ultra-high resolution weather and climate model framework to address multi-scale processes of the atmosphere and analyze the data from observations and these simulations to effectively arrive at inferences. General Circulation Models (GCMs), coupled ocean-atmosphere climate model and earth system model with emphasis on processes such as multiscale organization of organized convection and aerosol-cloud-radiation feedbacks, were employed. The group engaged in the field of multiscale problems in climate sciences, lithosphere-hydrosphere-atmosphere-ionosphere interactions and computational geodynamics. Since March 2016, our research foci expanded to include multi-scale earthquake dynamics, land-form evolution processes, multi-scale modelling of deformation processes and seismo-ionospheric coupling.*

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## 4.1 Teleconnection between all India rainfall and north-west Pacific

Recent years have witnessed large interannual variation of monsoon rainfall over India. This study attempts to understand the dominant factors contributing to variability of monsoon rainfall. A high resolution Atmospheric General Circulation Model (AGCM) forced with observed Sea Surface Temperature (SST), which shows marked skill compared to IPCC AR5 models, in simulating important features of Asian summer monsoon, interannual variability and extremes of all-India rainfall (AIR) and all essential aspects of teleconnection with the Pacific, is employed to investigate the mechanism responsible for rainfall variability. Variability of AIR is found to have the strongest link with the variation of rainfall over the northern parts of the West Pacific Ocean (NWTP), with deficits (excess) over India associated with enhancement (suppression) of rainfall over NWTP. This relationship is maintained through the meridional meandering of subtropical westerly jet (SWJ) stream. Consistently, in years with large excess/deficit in June rainfall, the strong link between all-India rainfall in June with convection over NWTP through meandering of SWJ is clearly manifested in the simulation by the high resolution global model. This work is part of CSIR 12$^{th}$ FYP project VACCIN which successfully concluded this year.

## 4.2 Local sea surface temperature-rainfall relationship over tropical oceans

Several studies of the simultaneous relationship of convection/precipitation over tropical oceans with the local sea surface temperature (SST), for the monthly scale, have shown that the propensity for deep convection/high precipitation is high for SST above about 27.5°or 28°C (which has been called the threshold), and low for lower SSTs. For warm oceans for which SST is maintained above the threshold such as the Bay of Bengal (BoB) and South China Sea (SCS), for each SST, there is a large variation of convection/precipitation and the SST-precipitation relationship is rather weak. A recent study has shown that, for BoB and SCS, for the daily scale, when the precipitation is assumed to lag behind the SST by a few days, the mean precipitation increases with SST. From this, it has been deduced that for these warm oceans, an increase in SST is associated with an increase in precipitation. However, we find that for BoB/SCS, as for the monthly scale, for the daily scale with appropriate lag, there is a large scatter around the curve depicting the variation of the mean precipitation with SST. This curve cannot be considered to be representative of the SST-precipitation relationship, as only a small fraction of the precipitation variance is explained by it. Hence we suggest that the conclusion that precipitation over these warm oceans increases with SST, based on the variation of the mean precipitation with SST, is not justified. This analysis is part of CSIR 12$^{th}$ FYP project VACCIN.

## 4.3 High-resolution climate change projections through dynamical downscaling

The coarse resolution General Circulation Models (GCM) has limitations in capturing the regional characteristics of Indian summer monsoon rainfall distribution, especially representation of Western Ghats narrow orographic rainfall. This is partly due to the deficiencies in the representations of the small-scale physical processes such as turbulence, small-scale convection, boundary layer fluxes, radiative effects, etc. And also the orographic gradients are resolved less accurately in the coarse resolution models, hence that can cause the unrealistic orographic precipitation in the model. To overcome these problems, with a dynamical downscaling technique, in which a higher-resolution regional climate model (RCM) is nested into the global GCM. We have implemented a very high-resolution non-hydrostatic RCM driven by realistic boundary conditions for Indian region. This high-resolution RCM simulation datasets can be used for many practical applications and are crucial for assisting the impact assessment.

Many current state-of-the-art coupled GCMs are facing challenges in simulating the Indian Summer Monsoon (ISM) rainfall and ISM rainfall is the most important feature during the season. For obtaining the more realistic boundary conditions, we have selected one of the IPCC AR5 models, that model is reasonably well comparable with the observation in almost all the present day physical as well as dynamical features. Studies have shown that, the high-resolution RCM performs very well given the large-scale forcing by the imposed boundary fields. Hence the performance of the RCM will always be limited by the quality of these driving GCM fields. We prepared historical (for present-day) data as well as the RCP8.5 (for future) data and made ready as the input of the RCM. We have done the longer simulations only after an intensive sensitivity simulations and analysis to obtain the suitable configuration for our RCM to give good simulation of monsoon over the Indian region. Since our study is focused on Indian region, we have selected different domains to serve the purpose. We have analyzed the longer period simulation of RCM to understand the model capability in simulating the present-day climate, which reveals that it is capable of capturing numerous regional details. The rainfall during the summer monsoon season over Indian region also compared with the IMD observed rainfall climatology. We found that the spatial heterogeneity of the ISM as well as the magnitude of the all India rainfall is well comparable. This implies that our RCM can be effectively used to extract very useful high-resolution climate change projection information for summer monsoon over India. This work is part of the grant-in-aid project funded by Govt, of Kerala.

## 4.4 Forecast of monsoon-2017 using CFSv2

The Indian Summer Monsoon (ISM) that occurs between June and September accounts for more than 70% of the annual rain over the Indian subcontinent. The spatial and temporal progress of monsoon over the subcontinent is important for agricultural planning, food production, hydroelectric power generation and lives of the billions of people of the country. The variable nature of monsoon over the years forces us to have a good prediction of the monsoon. We would want to get an accurate estimate of the monsoonal flow rather than to only satisfy ourselves with statistics and probability of occurrence of rain events. This lack of certainty which is fundamental to physical systems is utmost reflected while using climate models for prediction purpose.

Prediction of ISM has always been associated with sensitivity to initial conditions pertaining to the capricious behavior of climate system. This can be regarded as a classic example of prediction problem as was described by Edward N Lorenz. Given the fact that high resolution can take care of sub-grid scale processes which include the cloud and convection genesis within a climate model, it is imperative to look into the prediction with high resolution and with the right choice of initial condition. We at CSIR-4PI took into account these factors and did a forecast for the summer monsoon season of 2017 making use of the available computing facility at CSIR-4PI. The initial conditions were derived and forecasts were done using a total of 24 initial conditions. The runs were carried out at a resolution which corresponds to a grid resolution of approximately 40km. This large ensemble of forecast runs allows us to look into the initial condition dependency of simulations. This also enables us to look into the evolution of various local and remote factors that are responsible for determining the ISM. The runs show the predictability barrier or the spring barrier and a slow drift towards a much more stable forecast as we approach the monsoon season.

A prediction is useful if it has maximum lead time in predicting the monsoon season and so our attempt is to look for the best possible prediction with maximum lead time. Further analyses will be carried out to look into other characteristics of the ISM to further obtain a clear idea about the season's rainfall. This work is part of a collaborative project.

## 4.5 Aerosol-monsoon relationship over the Indian region

Atmospheric aerosols can cause significant alteration in the energy balance of the atmosphere and the earth surface by scattering and absorbing the incoming solar radiation (direct effect), and strongly influence the processes of formation of clouds and precipitation (indirect effect).

There are two types of Indirect effect:1) First Indirect effect or Twomey effect, 2) Second Indirect effect or Albrecht effect. In first indirect effect refers an increase in aerosol concentration can increase the reflectivity of the shallow clouds due to increase in cloud condensation nuclei (CCN); whereas the total liquid water path is constant. In second indirect effect due to increase in CCN the droplet number concentration increases and the effective radius decreases. These effects can increase total liquid water path by reducing the drizzle production.

Indian summer monsoon precipitation serves as a lifeline to our country. The total rainfall during the monsoon season is defined by the cumulative rainfall during June–September (JJAS). All-India summer monsoon rainfall shows considerable interannual variability. Its variability is characterized by the intraseasonal periodicity of about 30–60 days, which is essentially the demonstration of similar periodicity of the cloud organization, northward propagation and dissipation. Aerosols can influence monsoons on multiple timescales. Aerosol-monsoon relationship is highly complex due to the combined effects of microphysical and dynamical impacts of both regional and remote aerosol radiative forcing connected with meteorological forcing.

This study investigates the influence of aerosols on the Indian summer monsoon and characterizes their difference in drought and excess summer monsoon years using satellite data sets. Aerosols and clouds interact strongly in microphysical processes and this interaction depends on meteorological conditions. Data from the MODIS instrument for aerosols and cloud parameters are used. Aerosol optical depth or AOD, which is a measure of extinction of incoming solar radiation, serves as proxy to atmospheric aerosol loading is the main aerosol parameter used for this study. Cloud parameters such as cloud effective radius (CER), cloud optical thickness (COT), cloud top height (CTH), cloud water path (CWP) are also analyzed for this study. This study focused on two regions All India and Core Monsoon Zone. To understand the interaction of aerosol on Indian monsoon, we carried out detailed analysis of daily, monthly, seasonal and spatial variation of atmospheric aerosols over the study region.

During drought years AOD is found to be higher over Indian region compared to excess monsoon years. The total effect of aerosols causes reduction of summer rainfall but with distinct differences in their impact during strong and weak summer monsoon years, due to the changes in clouds, radiation, large-scale circulation, and convection. The comparison of anomalies of COT, CER, CTH during drought monsoon and excess monsoon shows, significantly lower values during drought monsoon while AODs are higher, implying an association between aerosols and clouds, and possibly an evidence for the indirect radiative effect of aerosols on clouds. From this study we can observe the variation of cloud properties during contrasting monsoon years are in opposite way. The correlation analysis of AOD and rainfall shows, aerosols has a significant role in rainfall formation during extreme drought years. Further analysis required to explain the mechanism of how aerosols modulate the rainfall during the monsoon time over Indian region. This work is part of the grant-in-aid project supported by MoEFCC.

## 4.6 Climate change impact on convectively coupled equatorial waves

Convectively Coupled Equatorial Waves (CCEWs) are important class of propagating disturbances which affect tropical mean convection and climate. They produce prominent intraseasonal fluctuations over tropics. Outgoing Longwave Radiation (OLR) data from observation and a high-resolution 20-km global climate model projection runs are analyzed to document the changes in the structure and propagation characteristics of CCEWs in future climate change scenarios. This work is funded by CSIR 12$^{th}$ FYP project VACCIN.

## 4.7 Application of the new algorithm for TRMM latent heating data

Even though Tropical convective precipitation systems have major role in the global climate system, our understanding of it is very poor because of not only its complexity in spatial and vertical distribution but also having very short lifespan for such systems. Diabatic heating estimates used in this study are from TRMM – PR utilizing the Spectral Latent Heat (SLH) algorithm. We are taken this level 2 swath data and converted it into gridded using nearest neighbour algorithm. From this generated data we analysed the four dimensional distributions (including time) of the apparent heat source ($Q_1$) – radiative heating ($Q_R$), apparent moisture sink ($Q_2$) and Latent heating in relation with the near Surface Precipitation rate and Storm top height. These resultant data set clearly explains the major characteristics of Tropical convection. Also we developed a vertically integrated $Q_1 – Q_R$, $Q_2$ and Latent Heat utilizing a new algorithm build on a time based rms weighting function. We examined the diurnal variation over tropics to analyze the latent heating and corresponding rainfall characteristics.

## 4.8 A Study on convective cyclonic systems using Megha-Tropiques data

Measurements from onboard Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie (SAPHIR) the low inclination Megha-Tropiques satellite with frequent daily revisits provide a valuable dataset for investigating the variation of tropospheric relative humidity in the tropical region. SAPHIR retrieved Level 2 data for atmospheric Relative Humidity is from the level 1000 hpa to 100 hpa helps to get a vertical variation of tropospheric Relative Humidity, which is provided in six averaged layers (1000-850 hpa, 850-700 hpa, 700-550 hpa, 550-400 hpa, 400-250 hpa, 250-100 hpa). The SAPHIR retrieved relative humidity data shows better correlation after bias correction with respect to global radiosonde data for all the months and for all the six layers. The correlation for the month of October, where we have calculated both the Correlation Coefficient (CC) and Regression Coefficient (RC) SAPHIR retrieved layer averaged relative humidity data has been used for the period of four years (2012-2015) to study the convective cyclonic systems occurred over Bay of Bengal (BOB) and Arabian Sea (ARS). For this study, total 14 cyclonic systems are selected.

## 4.9 Estimation of regional Vertical Land Motion (VLM) to constrain the sea level rise

The estimates of Mean Sea-Level (MSL) rise estimated using past tide-gauge data previously by various researchers along the coast of India indicate a rise of slightly less than 1mm/yr. It was also observed in earlier studies that the rate of vertical land movements need to be incorporated in order to identify the actual cause for the changes in Sea-level rise – i.e. either due to Global warming or Vertical Land Motion (VLM). The VLM may be of tectonic and non-tectonic origin, viz. deformation of the crust due to Tectonic activity, Glacial Isostatic Adjustment (GIA), seasonal deformation of the crust due to mass loading including atmospheric loading, local uplifts in Earth's solid surface due to the anthropogenic groundwater withdrawal etc. Recent modelling studies showed that the response of VLM to the cumulative groundwater loss from the continents from the year 1930 to 2015 depressed the relative sea level in southern Asia. An accurate estimation of VLM is vital to decouple the impact of land motion from sea level changes. At present, in India, sea-level changes are estimated by only correcting the modelled GIA from the tide-gauge measurements. Considering the importance of correcting the VLM in order to obtain the realistic sea-level change, a component on geodetic data analysis to estimate the VLM at various islands of Indian ocean, primarily Lakshadweep Islands was included under CSIR 12$^{th}$ FYP project VACCIN. As there are no direct measurements available from Lakshadweep Islands, we have modelled the GIA over this region and estimated the tectonic and non-tectonic vertical land motion using GPS (Global Positioning System) and GRACE (Gravity Recovery And Climate Experiment) measurements at an Indian ocean island site (Maldives) which is part of Chagos-Laccadive Ridge and at few inland sites (Bangalore and Hyderabad) in India. Lakshadweep Islands and Maldives are part of the Chagos-Laccadive Ridge.

Results show that the rate of vertical land motions are comparable with the sea-level changes calculated from Indian tide-gauge data. The seasonal variation in vertical land motion is a crucial parameter to constrain regional sea-level changes. The results also emphasise the importance of continuous mode geodetic observations at Lakshadweep Islands and also to extend the observations to West and East coast of India including Andaman and Nicobar Islands.

## 4.10 Establishment of continuous mode geodetic observatory to study the Vertical Land Motion (VLM) for constraining the sea level rise

The analysis of geodetic data carried out revealed the importance of continuous mode geodetic observations at Lakshadweep Islands. Based on the results of the preliminary study, as part of 12$^{th}$ FYP VACCIN project, a continuous mode geodetic observatory was set up at Kavaratiti, Lakshadweep Islands. A GNSS antenna was fixed on a concrete pillar and continuous mode observation was kick started. This set up also enabled with a data streaming facility which enables it to be used as a base station for GPS based land surveys. Continuous observation will be useful to study the behaviour of the tectonic and non-tectonic motion of the island and it will be used to constrain the regional sea-level change combining it with the tide-gauge recordings.

## 4.11 Lithosphere-Atmosphere-Ionospheric Coupling (LAIC): A multi-scale approach

The coupling process between Lithospheric processes, mainly seismic events, and Ionosphere is a multi-scale process involving multi-physics in different length and time scales. This multi-scale process can be divided broadly into three main categories viz. (i) Coupling between ionosphere and lithosphere prior to a seismic event (ionospheric precursors); (ii) Co-seismic ionospheric disturbances (CID) induced by shock, acoustic and Rayleigh waves; and (iii) Ionospheric perturbations induced by tsunamigenic Atmospheric Gravity Waves (AGW). The ionospheric perturbations associated with seismic events became well known after the 1964 Alaskan earthquake. Multitude of ionospheric observations and data explosion in the recent decade further proved the strong coupling between seismic events and ionosphere. However, the physics of Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) is yet to be well understood. In order to understand the multi-physics processes of the LAIC, a multi-scale modelling approach is initiated as part of the Multi-Scale Modelling Programme. The model will be validated through the integrated ionospheric Total Electron Content (TEC) or Ionospheric electron density derived from satellite based microwave soundings.

As part of this initiative, we have developed a software module IONPEST (IONospheric Perturbation ESTimator) for the computation of geometry free ionospheric perturbation from satellite borne multi-frequency microwave soundings. The satellite motion introduces sharp spatial variations in the TEC measurements which mimics the ionospheric perturbation. Hence it is important to remove the geometric influence in order to obtain the real signal. This newly developed module successfully eliminates the geometrical errors and provides the ionospheric perturbations free of such geometric influences. The geometry free ionospheric perturbations will be useful to study the response of the ionosphere to various phenomena ranging from space weather to seismo-ionospheric coupling.

Using IONPEST, we have studied the co-seismic ionospheric perturbations associated with the 25 April 2015 Nepal Earthquake which created wide-spread damage. We have analysed both near-field and far field geometry-free ionospheric perturbations and found that the perturbation exactly follow the rupture propagation pattern and also reduction in amplitude with distance from the epicentre.

## 4.12 Seasonal hydrologic deformations over North-East India and Nepal Himalayas

Water plays pivotal role in shaping weather and climate and the redistribution of water causes deformation of the earth surface which can be detected using space based geodetic techniques. Monsoon rainfall over Indian subcontinent causes large hydrological mass change and produces seasonal deformation which can be estimated using satellite based geodetic observations. We have modelled the hydrologic deformation in North-East India and Nepal Himalayas which covers Ganges-Brahmaputra region using the gravity variations observed by GRACE (Gravity Recovery and Climate Experiment) satellites and compared it with GPS observations for the time period of 11 years (2002-2013). Three statistical methods (i) Correlation (ii) Weighted Root Mean Square Reduction and (iii) Nash-Sutcliffe Efficiency (NSE) were employed for comparing GRACE modelled and GPS observed seasonal hydrologic deformation. The results suggest that GRACE and GPS agree more in North-East India than in Nepal Himalayas. It is also observed that vertical component of both GRACE and GPS matches better than that of horizontals which is probably due to the sensitivity of horizontals to the local effects.

## 4.13 Sea level changes and geodetic variations due to GIA

We used numerical solutions of sea level equation (SLE), that describes the sea level and Earth deformations associated with Glacial Isostatic Adjustment (GIA), for a spherical, layered, non-rotating Earth, with Maxwell viscoelastic rheology to model the past and present sea level variations in response to the melting of late-Pleistocene ice sheets. We predicted the present day geodetic vertical and horizontal surface displacements and the gravity variations on a global and regional scale and compared it with the available geodetic observations from tide gauges, satellite altimetry, gravity variations and crustal deformation values, for validation. It was observed that the present Earth surface geodetic variations are directly affected by the melting of past and present ice sheets and is also sensitive to the melt water component of the surface load.

We have assumed few approximations like, a linear incompressible rheology and a spherically undeformed Earth without any lateral variations in rheology. In addition to this, effects of the Earth's rotation upon sea level variations, horizontal migration of shorelines in response to sea level changes which lead to crude approximations in areas of shallow bathymetry, local effects like subsidence, slumping or sediment loading, ocean or ice dynamics and possible steric sea level variations or effects due to these are not taken care in this model.

Initially we computed the viscoelastic load-deformation coefficients for a layered Earth model defined by its rheological properties, followed by solving SLE numerically for predicting surface geodetic quantities. The numerical results present relative sea level variations driven by GIA since last glacial maxima (LGM), 21 kyrs before and its viscoelastic response till present. This work is part of $12^{th}$ FYP Project VACCIN.

## 4.14 Multi-scale simulation framework for earthquake physics studies: seismic-cycles at plate-boundary zones

We tested the accuracy and performance of a multi-scale simulation framework for earthquake physics using the CSIR-4PI 350TF HPC cluster through a rigorous benchmarking process. This 3D numerical code is a portable, scalable software for simulation of crustal deformation involving spatial scales ranging from meters to hundreds of kilometers and temporal scales ranging from milliseconds to thousands of years. We tested these codes for quasi-static crustal deformation and evaluated the relative performance of different types of basis functions, numerical integration schemes, and model discretization for multi-scale crustal deformation modelling applications. In addition, we evaluated the efficiency and scaling of the numerical codes. These benchmarks were good test problems, in which we performed simulations comparable to actual seismo-tectonic settings. These benchmarks were performed at various resolutions using different element types.

By comparing the runtime and efficiency for different resolutions and element types, we evaluated the combination which will be the best representative of the tectonic problems of our interest. We considered a quasi-static interseismic and coseismic deformation in 2D for a subduction zone benchmark problem which computes the coseismic relaxation of stresses based on the 2011 M9.0 Tohoku earthquake, off the east coast of Japan. We modelled the earthquake rupture involving coseismic slip along the interface between the subducting slab and the continental crust and uppermost portion of the mantle below the continental crust. We used standard analytical solutions to apply the boundary conditions and to compare against the numerically-computed elastic solution.

## 4.15 Indo-Burman Ranges: Myanmar sliver deformation and the locked sinking Indian lithosphere

The Indo-Burmese arc, eastern boundary of Indian tectonic plate is formed from the oblique subduction of Indian plate under Eurasia. This region is the transition between the main Himalayan collision belt and the Andaman arc where the Indian plate is currently subducting under Eurasia. The obliquity causes strain partitioning which leads to generation of the sliver plate, the Burma

Plate. The Indo-Burmese arc and the Sagaing fault represents the western and eastern boundary of this sliver plate. Various researchers has suggested that the subduction might have stopped recently or continues relatively in an aseismic fashion, which is primarily seen from the compressional stress orientations in a NNE direction instead of downdip direction. The stress inversion of focal mechanisms shows distinct stress fields above and below 90 km along the subducting Indian slab. In the segment lesser than the 90 km deep, active tectonics is controlled by NNE oriented horizontal plate tectonics forces and below to this depth is driven by tensile forces due to the gravitational loading of the subducted slab. Because of poorly determined hypocentre locations of earthquakes in this region, the geometry of subducting slab is not well resolved. The joint hypocentre location studies show that the dip is 15-20° at 40-60Km depth, then steepens to 30-50° below the 60Km. The partitioning of Indian-Eurasia motion along the Indo-Burmese arc and Sagaing fault region is considered as reason for earthquakes in this region. The relative motion 36mm/yrs between India and Eurasia is partitioned by ~20mm/year across the Sagaing fault through dextral movement.

## 4.16 Crustal deformation followed by the Mw 7.7 January 26, 2001 Bhuj intra-plate earthquake

To have a better understanding on the deformation followed after the 2001 Bhuj earthquake, we adopted a non-linear post seismic relaxation method and analyzed the co-seismic and post seismic deformation scenarios. We made use of seismic and geodetic data to understand the distribution of slip during the Bhuj earthquake. According to our slip distribution model, Bhuj earthquake ruptured Earth's crust from the surface to a depth of 31 km. The dip angle of the main fault plane is 51 degree and strike 82 degree. The model shows a remarkably compact source with slip of ~12.9m occurring in a ruptured patch which is ~40x40 sq. km wide. The aftershocks were concentrated at the edges of the slipped patch, suggesting that they are related to stress concentrations on the margins of the coseismic rupture. The maximum uplift is located about 15 km north of the reported epicenter matches with our predicted surface uplifts values of our model. Using this stress preturbation model, we modelled various scenarios of post-earthquake relaxation patterns for the Bhuj region.