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Land surface processes over Indian summer monsoon region: A review

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सार - पृथ्वी की सतह, द्रव्यमान, नमी और संवेग के आदान-प्रदान के माध्यम से निरंतर वातावरण को प्रभावित कर रही है, जिससे ऊर्जा और जल चक्र में परिवर्तन हो रहा है। इसके माध्यम से, पृथ्वी की सतह मौसम और जलवायु प्रणालियों को प्रभावित करती है। भूमि की ये प्रक्रियाएँ भारतीय मानसून क्षेत्र (IMR) जैसे विविध सतह विशेषताओं वाले क्षेत्रों पर हावी हो जाती हैं। मौसम और जलवायु के पूर्वानुमान का एक अभिन्न अंग होने के नाते, भारतीय ग्रीष्मकालीन मॉनसून (ISM) से जुड़ी भूमि सतह प्रक्रियाओं को संख्यात्मक मौसम पूर्वानुमान (NWP) मॉडल में समझने और वास्तविक रूप से प्रस्तुत करने की आवश्यकता है।

भारतीय ग्रीष्मकालीन मॉनसून एक विशाल प्रणाली होने के कारण दोनों महाद्वीपों और उष्णकटिबंधीय महासागरों की सीमा से प्रभावित होता है। यह बड़े पैमाने के क्षेत्रों और छोटे पैमाने पर संवहन गतिविधियों के बीच अरैखिक अन्योन्य क्रिया के कारण एक जटिल प्रणाली है जो स्थानीय स्तर की भूमि की सतह की विशेषताओं और वातावरण के साथ मिलने से बहुत प्रभावित होती है। वर्तमान समीक्षा लेख भूमि सतह प्रक्रियाओं के हाल के विकास और भारतीय ग्रीष्मकालीन मॉनसून प्रक्रिया अध्ययन के लिए उनके उपयोग पर केंद्रित है। इस शोध पत्र में भूमि की सतह के मॉडल के विकास, अत्याधुनिक भूमि की सतह के आमेलन प्रणाली (LDAS) और एनडब्ल्यूपी (NWP) मॉडल में उनके अनुप्रयोगों पर चर्चा की गई है।

ABSTRACT. The earth's surface continuously interacts with the overlying atmosphere through the exchange of mass, moisture and momentum, thereby altering the energy and water cycles. Through this, the earth's surface affects regional energetics, which *via* scale-interaction influences weather and climate systems. The land surface feedbacks are dominant over the Indian Monsoon Region (IMR) and exert impact on the atmospheric responses such as convection and precipitation through boundary layer coupling. As a result, the land surface processes associated with Indian Summer Monsoon (ISM) need to be understood and realistically represented in Numerical Weather Prediction (NWP) and regional/global climate models.

The ISM is a multiscale system influenced by the boundary forcing from both the continent and tropical oceans, as well as from various boundary layer feedback mechanism. The ISM and associated rainfall is a complex system owing to non-linear interaction between large-scale fields and small-scale convective activities. The ISM is notably influenced by the local and regional scale land surface interactions. This paper reviews the recent developments related to land surface processes and their application to ISM process studies. The evolution of land surface models, state-of-art Land Data Assimilation Systems (LDAS) and their applications in NWP models are discussed.

Key words – Indian summer monsoon, Land surface processes, Land data assimilation system, Ensemble Kalman filter, Soil moisture.

1. Introduction

The monsoon is characterized as a synoptic-scale atmospheric circulation system manifested by land-atmosphere-ocean interaction between land and oceans in a seasonal cycle (Webster *et al*., 1998). The temperature gradient between the continents and oceans, together with the Coriolis force causes a semi-annual reversal of wind direction and it affects the earth's weather and the climate system to a larger extent (Wang and Ding, 2008). Among the monsoon systems in the world, the Indian Summer Monsoon (ISM) is one of the most spectacular phenomena that contribute to ~80% of the Indian annual total rainfall (Jain and Kumar, 2012). The south Asian region exhibits unique physiographic features with Asian continent spread in the Northern hemisphere along with Indian Ocean water, which supports the development of intense thermal and moisture gradients. The resultant pressure patterns and the meridional circulations, along with the presence of the topographical effect of south Asia, aid the development of ISM. The monsoon system travels southwest direction and carries abundant moisture from the Indian Ocean and adjoining seas and precipitates over the Indian landmass from June to September. The ISM rainfall provides freshwater to various human activities such as agriculture particularly, for the Indian region where nearly ~60% of the population depends on agriculture and allied activities (Kekane, 2013). The agricultural production is important for the rural economy for livelihood and societal development (Naiyer *et al*., 2015) that contributes considerably to the country's Gross Domestic Product (GDP) (Gadgil and Gadgil, 2006). Because of the high economic impact and societal wellbeing, the prediction of ISM rainfall has been a major consideration for the meteorological community. One of the challenges identified for improving the ISM rainfall prediction is to develop an understanding of the complex land surface processes beneath the land-air-sea interactions (Niyogi *et al*., 2006; Pielke *et al*., 2011).

The ISM is primarily influenced by the surface boundary forcing from both the continent and tropical oceans. The role of oceanic feedback on the development of ISM is extensively documented in earlier studies (Sikka, 1980; Gadgil, 2003; Gadgil *et al*., 2007). There have been sustained efforts underway to improve the understanding and prediction of ISM precipitation at varying temporal scale (Singh *et al*., 2007; Saha *et al*., 2011; Rajesh *et al*., 2016; Nayak *et al*., 2018; Maurya *et al*., 2018; Mohanty *et al*., 2019a,b; Mohanty *et al*., 2019; Sinha *et al*., 2019). Initial studies related to the ISM often ignored the role of land surface processes on the monsoonal rainfall, energetics and associated process (Cadete, 1979; Sikka, 1980). In the 1960s, the role of the land surface processes on climate system was being considered in studies such as Manabe (1969). Subsequently, a number of land surface models (LSM) have been developed starting from the simple "Bucket" module to complex biophysical module, that includes carbon, energy, water exchange between land surface and atmosphere (Manabe, 1969; Deardorff, 1978; Mahrt and Pan, 1984; Dickinson *et al*., 1986; Sellers *et al*., 1986; Pan and Mahrt, 1987; Chen and Dudhia, 2001; Ek *et al*., 2003; Dai *et al*., 2003; Pitman, 2003). Incorporation of these enhanced land features contributes to improving simulations of precipitation across various temporal scales (Ek *et al*., 2003; Dai *et al*., 2003; Pielke, 2001).

Over the Indian region, the importance of land surface processes on weather and climate system is evident from results obtained in various recent studies (Dastoor and Krishnamutri, 1991; Singh *et al*., 2007; Krishnamutri *et al*., 2012; Paul *et al*., 2016; Osuri *et al*., 2017; Unnikrishnan *et al*., 2017; Nayak *et al*., 2018). For example, the role of land-atmosphere coupling strength in the south Asian monsoon region was examined by Unnikrishnan *et al*. (2017). Their study demonstrated that soil moisture (SM) is strongly coupled with the sensible heat flux over the Indian Monsoon Region (IMR) and thereby affects ISM rainfall variability. Paul *et al*. (2016) demonstrated that the land use land cover (LULC) changes cause a decrease in evapotranspiration and subsequent reduction in the recycled precipitation leading to the weakening of the ISM rainfall. Therefore, the role of the land and it's feedbacks need to be integrated for skillful prediction of short, medium and long-range systems over the IMR (Niyogi *et al*., 2018). Devanand *et al*. (2018) demonstrated that the improved representation of land-atmosphere interaction, in a regional model, supplements the moisture contributions from distant oceanic sources. Incorporation of unmanaged irrigation and paddy cultivation information of north-west India in a regional climate model leads to an increase in the monsoon precipitation during September (Devanand *et al*., 2019). Niyogi *et al*. (2010) have shown that agricultural intensification/irrigation has a significant feedback in explaining the reduce precipitation in the northwestern regions of India.

There have been studies demonstrating the role of land surface processes on the short-range prediction of ISM (Rajesh *et al*., 2016). Studies such as Baisya *et al*. (2017) found positive soil moisture-precipitation (S - P) feedback processes associated with Indian monsoon depression (MD) through control on evapotranspiration and moisture flux convergence. Recent research using advanced modelling framework have shown that the high-resolution soil moisture (SM) and soil temperature (ST) initialization in the mesoscale model has improved the simulation of Uttarakhand heavy rainfall (Rajesh *et al*., 2016), severe convective events (Osuri *et al*., 2017) and MD related heavy rainfall processes (Nayak *et al*., 2018).

Over the past two decades, data assimilation techniques have evolved and widely been used to improve model initial conditions through the incorporation of conventional (*in situ*) and non-conventional (satellite-based) observations (Routray *et al*., 2010). With the growing Doppler Weather Radar (DWR) network across the Indian region, Prasad *et al*. (2014) demonstrated that the assimilating DWR observations could improve the thunderstorm simulations; but the performance was constrained due to improper initial land surface conditions. The errors in the land surface observations, due to the limited direct measurements, are one of the major limitations to representing accurate moisture processes associated with land surface feedbacks (Robock *et al*., 2000). These errors in the surface moisture fields lead to notable uncertainty in the coupled meteorological forecasts. Since observations of land conditions are limited, it becomes necessary to parameterize the different processes and represent the energy-water exchanges through land surface models (LSMs). The LSMs have exhibited remarkable robustness across different geographical regions and landscape conditions and an ability to provide regionally realistic surface conditions for modeling studies. The LSMs can be run in a pre-prediction or spin-up mode using offline meteorological information to generate gridded soil moisture/ temperature fields. These offline simulations have been at the heart of developments such as the high-resolution land surface data assimilation system (LDAS; Chen *et al*., 2007). Thus, the LDAS is a regional LSMs that is forced with surface meteorological analyses/observations and provides gridded fields of land states such as SM, ST and turbulent surface fluxes (Mitchell *et al*., 2004; Rodell *et al*., 2004; Chen *et al*., 2007; Osuri *et al*., 2017; Nayak *et al*., 2018). Studies such as Osuri *et al*. (2017) have shown that the LDAS-based land initialization can provide a positive impact of realistic soil conditions on mesoscale simulation of severe thunderstorms over India. The LDAS integration within coupled models has been of value within a monsoon modeling framework for improved prediction skills of variety of weather systems such as heavy rainfall events, monsoon depression (Rajesh *et al*., 2016; Osuri *et al*., 2017; Nayak *et al*., 2018, 2019). These studies highlighted the significance of land-atmosphere interaction and their influence on weather and regional climate systems. The land initialization and land model representation is an evolving area in India and highlights the need for this review. The present paper seeks to provide a review on development, application of land models and their impact on extreme weather and climate systems in the Indian context.

2. Land-atmosphere feedback processes

Earth's surface receives water and energy in the form of precipitation and radiation from the atmosphere and surface in turn exchanges energy and moisture to the atmosphere in the form of turbulent surface energy fluxes. There are complex sets of interactions between the earth's surface and the overlying boundary layer through various processes and feedback mechanisms (Pielke *et al*., 1998). Fig. 1 depicts one such schematic of S - P feedback processes in the weather and climate system. The S - P feedback can be considered in various pathways. One aspect could be manifested as in Fig. 2.

In recent years, the understanding of S - P feedback processes has been studied at multiple temporal scales. Particularly for the sub-daily to daily scales, the S - P feedback mechanism can be assessed through the influence of SM state on atmospheric boundary layer and convective initiation. Studies investigating the effects of SM on rainfall have found both positive and negative feedbacks (Alfieri *et al*., 2008; Guillod *et al*., 2014; Duerinck *et al*., 2016). Positive spatiotemporal feedback is the increase in SM leads to cloud formation and precipitation, often under low stability conditions. While negative spatiotemporal feedback usually requires high sensible heat that permits sufficient turbulent mixing (Hohenegger *et al*., 2009) and leads to evaporation but not a direct increase in local rainfall. The emerging understanding related to the dynamical feedbacks of SM heterogeneity (Taylor and Lebel, 1998) highlights its role in the initiation of convection over the drier soil through mesoscale atmospheric circulation and an increase in convergence (Taylor *et al*., 2011). The heterogeneities in SM can cause convective rainfall events over anomalously drier regions (Guillod *et al*., 2015). In the context of the ISM, the S - P feedback is expected to be active especially post-onset and needs to be studied more extensively in the future (Krishnamurti *et al*., 2012).

The land-atmosphere coupling strength is important for the initiation of convection and precipitation. The land-atmosphere coupling strength is described as the extent to which anomalies of soil surface state can affect precipitation generation and other atmospheric processes. As a part of land surface feedback studies, the land-atmosphere coupling strength was extensively examined through the Global Land-Atmosphere Coupling Experiment (GLACE) (Koster *et al*., 2004). Their research suggests that the coupling strengths varied across the globe and identified the region of Africa, central North America and India as the "hot spot" regions for the SM and precipitation coupling. These regions are primarily located between dry and moist climatic regimes in the transition zones with intermediate soil wetness. In the past five decades, there has been increasing progress on the land-atmosphere modeling and coupling (Koster *et al*., 2004; Wang *et al*., 2007; Wei and Dirmeyer, 2010; Zhang *et al*., 2011) through the development of wide range of land surface models as briefly summarized below.

3. Evolution of Land surface models (LSM)

The early LSMs assumed a simplified land surface model (LSM) known as the "bucket" model (Manabe, 1969). This model considers fixed soil properties and constant soil depth in which the "bucket" is filled with precipitation and emptied by evaporation. The excess rainfall that bucket cannot hold or a critical value is

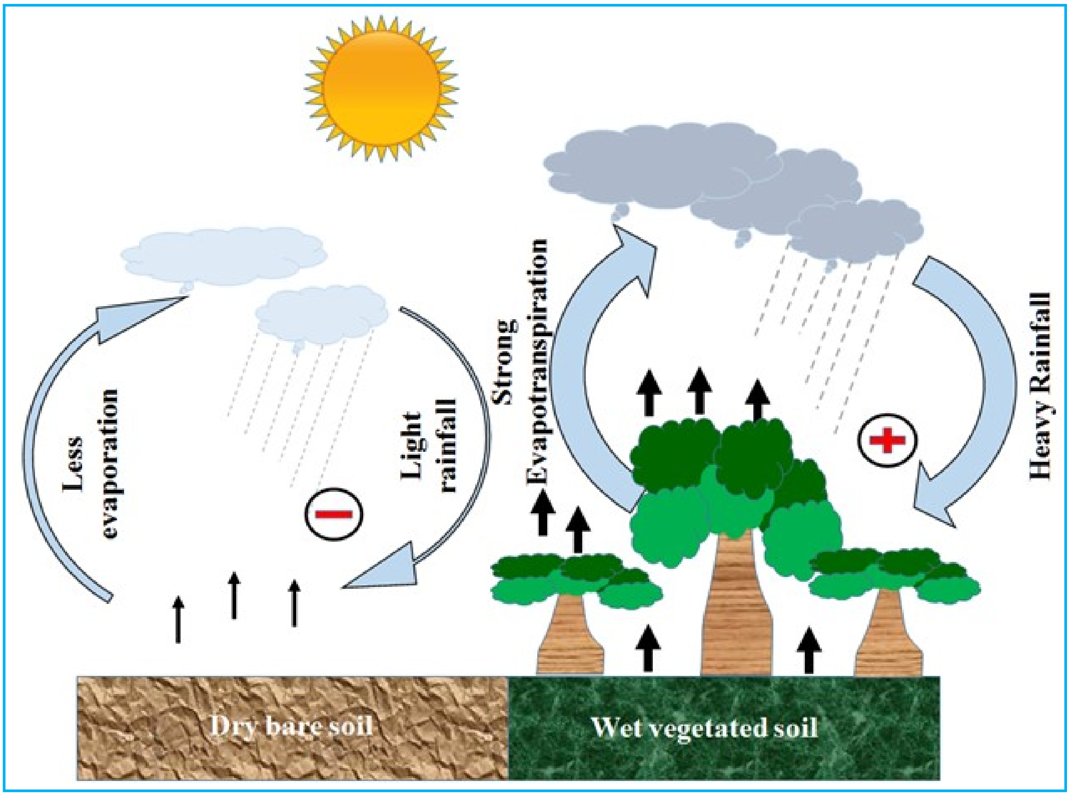


Fig. 1. Schematic of soil moisture-precipitation feedback processes associated with the weather and climate system. A positive soil moisture-precipitation feedback loop is shown at right side and negative feedback are shown in left side of the figure

considered as runoff. This model did not consider the transfer of heat in soils and assumed the evaporation rate to be a linear function of SM and potential evaporation (Penman, 1948). This "bucket" model is the first generation of the LSM. The performance of this LSM suffers from lack of realism and consideration of vegetation, canopy and associated surface processes. The "bucket" model was influential in introducing the land feedback for meteorological models but was insufficient to depict diurnal to multi-annual scale surface variability. The simplification of evaporation formulation (equation 1) was one of the major limitations of the first-generation schemes:

$$L = \beta\left(\frac{e^*(T_s)-e_r}{r_a}\right)\frac{\rho C_p}{\gamma} \tag{1}$$

where, $e^*(T_S)$ and e_r are the saturated vapor pressure at T_S and vapour pressure at a reference height, respectively. Also, γ is the psychrometric constant. ρ is the air density and C_p is the specific heat of the air and aerodynamic resistance is denoted as r_a. The term β ranges from 0 (dry) to 1 (saturated). However, a number of studies have asserted that the simple β-function is inadequate to capture the moisture feedback and there is a need to more explicitly model land surface processes (Seller *et al*., 1997). The NWP simulations, in particular, are impacted and show modest performance due to the use of such simple β-function in the LSM.

The second-generation LSMs explicitly consider the vegetation impact (Deardorff, 1978). These second-generation models consider the effect of vegetation on momentum, water and energy transfer and include this feedbacks by representing at least two soil layers. Some of the LSMs also explicitly distinguish between soil and vegetation-based moisture fluxes, while some aggregate their grid-based feedback to develop spatially/temporally varying surface fields. The radiation, surface energy balance feedback is represented using the properties of the vegetation canopies as typically being responsive to the photosynthetically active radiation (PAR) absorption wavelengths of 0.4-0.7 µm and reasonably reflective in the near-infrared (0.72-4 µm) (Dickinson *et al*., 1987). The Richards equation-based water transfer scheme and adoption of surface processes such as saturation/ infiltration, excess surface runoff are also parts of this development. Under this framework, a number of advanced LSMs such as Biosphere Atmosphere Transfer Scheme (BATS) (Dickinson *et al*., 1986) and the Simple

Biosphere (SiB) Model (Sellers *et al.*, 1986) have been constructed. The prime objectives of the BATS and SiB LSMs were to provide surface boundary conditions to the Global Climate Models (GCMs) (Henderson-Sellers *et al.*, 1993). A number of derivatives of these LSMs were developed through improvements in parameterizations, field observations based empirical improvements in the formulations, model intercomparison studies and computational advances. The second-generation LSMs enhanced the representation of various land surface parameterization and continue to be a core component of the NWP studies and not just GCMs (Niyogi, 2000).

The modification introduced in the evaporation/ transpiration term of the second-generation LSM is one of the major advancements over the first-generation models. In the second-generation LSMs, the land feedback in evapotranspiration is modeled explicitly as:

$$L = \left(\frac{e^*(T_s)-e_r}{r_c+r_a}\right)\frac{\rho C_p}{\gamma} \tag{2}$$

where, r_c is the canopy resistance. The equation (2) facilitates different treatment of the water flux between the soil and canopy including an interception. Equation (2) is fundamentally different from its equivalent first-generation LSM (equation 1) in which explicit consideration of vegetation canopy transpiration term r_c was omitted. The aerodynamic and canopy-related resistance terms are separated in the second-generation LSMs by including r_c in parallel with r_a.

Through the explicit representation of canopy processes, the second-generation LSMs could better represent the surface variability and simulate land surface interactions. Under this development, Noah LSM (Ek *et al.*, 2003) and its predecessor Noilhan and Planton (1989) model is widely used in many operational NWP centres. The Noah LSM considers various surface processes such as the multi-layer soil model (Mahrt and Pan, 1984), primitive canopy model (Pan and Mahrt, 1987), complex canopy resistance (Chen *et al.*, 1996), frozen ground physics (Koren *et al.*, 1999) and has proven its credibility for many weather simulations (Ek *et al.*, 2003; Lee *et al.*, 2016).

The second-generation LSMs have typically outperformed the first generation models and improved the modelling of surface-atmosphere interactions. Studies have demonstrated that with enhanced surface process representation, NWP models often show an improved precipitation forecast (Beljaars *et al.*, 1996). Studies such as Viterbo *et al.* (1999) also showed that better soil parameterization based models are essential for simulation of extremes in surface features such as extreme heat. The

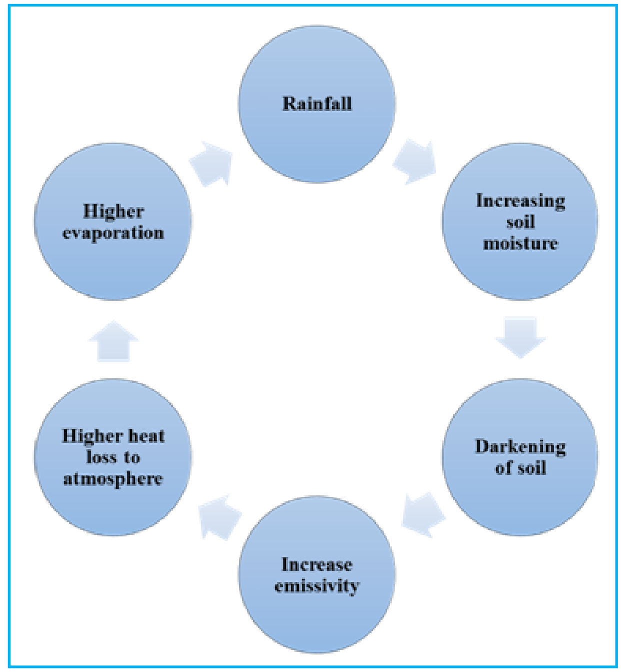


Fig. 2. Schematic of soil moisture-precipitation feedback pathways

improvements in the meteorological fields is attributed to the better simulation of surface energy balance, accurate simulation of mesoscale convergence features, boundary layer processes and cloud - convection processes.

The third-generation LSMs incorporate vegetation feedback using parameterizations that were developed off several plant physiological and ecological studies in the 1980s. An important conclusion building off the field and modeling studies was the recognition of the inclusion of an explicit canopy conductance improves the simulation of the evapotranspiration pathway and also addresses the issue of carbon uptake by plants. Plants use carbon dioxide, water, radiative energy for photosynthesis and the carbon uptake by the plant, thus constitutes a sink of carbon dioxide from the atmosphere. These features are of interest to the ecological and climate modeling community and led to the development of third-generation LSMs such as BATS2 and SiB2 (Sellers *et al.*, 1992, 1996; Bonan, 1995).

Even though the third-generation LSM framework was designed for climate studies, the interlink between the need for better evapotranspiration modeling and mesoscale convection meant that the detailed canopy models would be of relevance for short-term NWP modeling as well. Therefore, a framework that considers the simplified biophysical feedback of the third-generation models, as would be needed for evapotranspiration representation within NWP was felt necessary and that led to the development of land schemes such as the Noah-GEM model (Niyogi, 2000). Niyogi *et al.* (2009) demonstrated that the photosynthesis-based gas exchange model (Noah-GEM) could be efficiently coupled with short-term weather forecast models and the improved vegetation response directly enhanced NWP model performance particularly, for summertime rainfall predictions.

With the growing number of modeling approaches that incorporated modifications or different formulations to represent land surface feedbacks, there was a need to consolidate them into one set of modeling frameworks. Such a need led to the creation of NASA Land Information System (NASA LIS) which incorporates common meteorological forcing and architecture for running different LSMs (Kumar *et al*., 2008). Studies also showed that when using different modeling systems, no individual model adequately represents soil water exchanges with the atmosphere (Dirmeyer *et al*., 2006) and the multimodel ensembles yielded the most satisfactory performance. Such findings have led to the development of LSM with multi-physics options (Noah-MP) to mimic the multi-model behaviour (Niu *et al*., 2011; Yang *et al*., 2011). Recently, an explicit cropland-atmosphere interaction has also been added to Noah multi-physics model leading to the development of Noah-MP-Crop (Liu *et al*., 2016). In spite of such developments, the model prediction skill is intimately linked to the prescription of land initial conditions, which are difficult to obtain and necessitates the development of data assimilation products.

4. Land Data Assimilation System (LDAS)

The knowledge of land surface processes and associated variability is an essential component for weather and climate predictions. The land surface interactions are represented in most of the improved operational models globally through the incorporation of land surface schemes in their NWP models. However, NWP forcing errors accumulate in the surface and field stores, resulting in inaccurate partitioning of surface water and energy fluxes.

The realistic initial land surface state is also an essential factor for the enhanced reproduction of land-atmosphere coupling in numerical models. Because of the inadequacy of the land surface observations, realistic land initialization in the NWP models is a challenge (Robock *et al*., 2000). In what proved to a pathbreaking approach, Mintz and Serafin (1981) developed a monthly climatology of global SM using the observed precipitation and temperature. They used these climatological land fields in operational and research experiments. Over the years, this approach of developing land fields from climatology has continued to be the backbone of running land models in both operational and research setup (Suarez *et al*., 1983; Serafini and Sud, 1987).

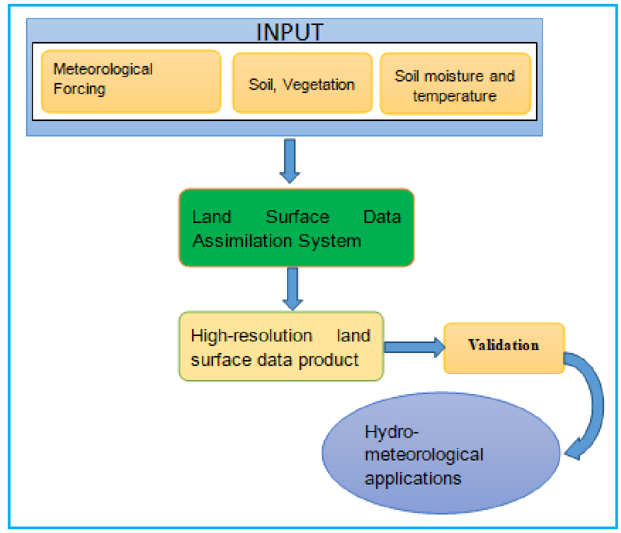


Fig. 3. Schematic flow chart of land surface data assimilation system

Over the years, the model resolution has steadily increased with better computational resources. The demand for increased resolution is also driven by the need to accommodate the representation of small-scale physical processes for skillful model performance. Therefore, the coarser-resolution climatological datasets often do not represent reality, especially in terms of capturing the surface heterogeneity. To that end, the generation of high-resolution land surface data products becomes a priority. The LDAS framework (Chen *et al*., 2007) provides an attractive option because the land model is forced with in-situ and satellite observations and analysis fields (as available) and conforms to the weather model grid structure.

A typical workflow of the LDAS system as used for the ISM domain is shown in Fig. 3. As mentioned, the LDAS systems estimate land surface conditions such as SM and ST at the surface and subsurface soil layers along with surface energy fluxes. Several LDAS systems are actively used in different modeling centers globally. Examples of LDAS products include, the North American Land Data Assimilation System (NLDAS; Mitchell *et al*., 2004), Global Land Data Assimilation System (GLDAS; Rodell *et al*., 2004), South American Land Data Assimilation System (SALDAS; Goncalves *et al*., 2006), High-Resolution Land Data Assimilation System (HRLDAS) (Chen *et al*., 2007), as well as the NASA Land Information System (LIS; Kumar *et al*., 2006). Among them, HRLDAS has been used over different parts

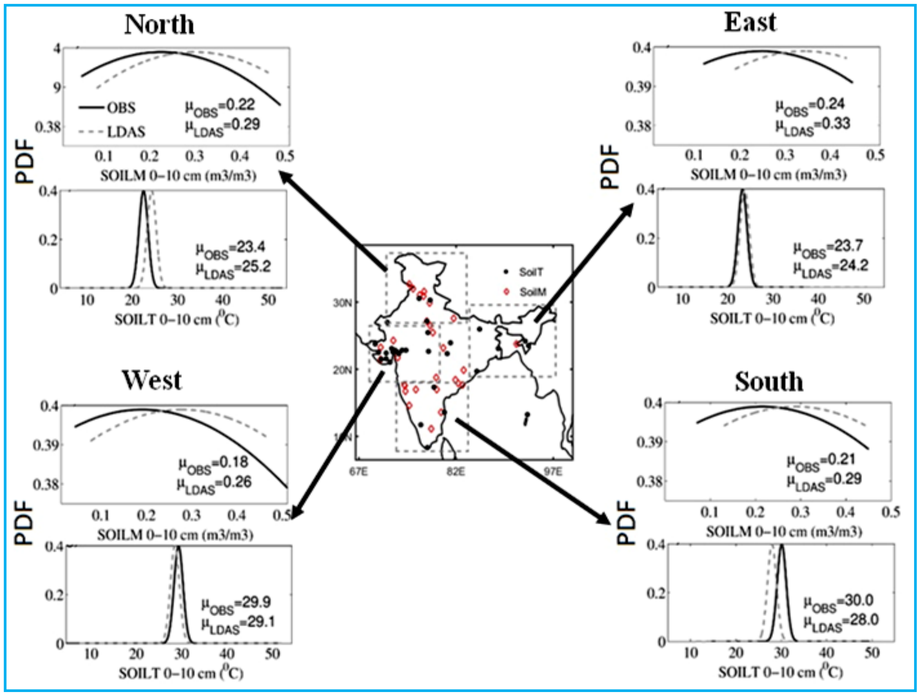


Fig. 4. Network of *In situ* observations used for validating LDAS products in the north, south, east and west regions of India, as representated in four boxes. The solid black circle represents (30) Agromet stations (for soil temperature) and the red diamond represents (30) AWS stations (for soil moisture). The normal probability distribution of observed and LDAS SM, ST for north, south, east and west regions are presented in four corners. The symbol 'μ' in the plots represents the mean and the source of the data are indicated in subscript

of the world as the derived land state provides ready initialization for the WRF suite (Lim *et al*., 2012; Osuri *et al*., 2017; Nayak *et al*., 2018).

The SM and ST fields have been generated over the Indian region as well by using the advanced LDAS system. For instance, Unikrishnan *et al*. (2013) generated SM and ST data at 0.5° × 0.5° spatial resolution for the period covering 2005 to 2010 using Noah LSM in a LDAS framework. Their study provided a helpful proof of concept for developing surface fields using LDAS over India. The study also highlighted that the 0.5° resolution SM and ST field was not adequate to represent surface heterogeneity, which is important to be captured in the Indian context for simulating mesoscale convection. Osuri *et al*. (2017) developed LDAS-based land conditions at 3 km horizontal grid spacing for eastern parts of India, a region that is prone to severe convection. In addition to creating the surface fields, their study extended the analysis to demonstrate the value of the improved LDAS based SM and ST products to simulate pre-monsoon thunderstorms. Building off that successful implementation, Nayak *et al*. (2018) developed a 4 km grid spaced, 3-hour temporal resolution-based SM and ST dataset from 2000 to 2014 covering the entire Indian mainland. These SM and ST products were validated with different *in-situ* datasets such as Automatic Weather Station (AWS) observations for the Indian summer monsoon months (Fig. 4). The Fig. 4 represents the normal probability distribution of SM and ST from LDAS and observations for varying geographical locations such as north, east, west and south regions across India. The results indicate that the soil is climatologically wettest in the east (μ_{obs} = 0.24 and μ_{LDAS} = 0.33) and relatively drier in the west (μ_{obs} = 0.18 and μ_{LDAS} = 0.26) and south (μ_{obs} = 0.21 and μ_{LDAS} = 0.29) regions during summer monsoon season. The LDAS provides a relatively wet soil condition for all sub-regions during monsoon season. The LDAS ST in the east (bias ~0.5 °C) and west (bias~ -0.8 °C) regions agree well with observations while it tends to underestimate the observations (bias ~-2.0 °C) in the south and overestimated in the north (bias ~1.8 °C).

Nayak *et al*. (2019) have demonstrated that the LDAS derived data product has reasonable skill in simulating SM and ST. Their study suggested that the skill could be further improved by using local soil properties such as soil porosity and soil field capacity. Furthermore, Nayak *et al*. (2018) have shown that the high-resolution LDAS SM is superior to the coarser resolution GLDAS product when compared with satellite-derived products of the European Space agency's climate change

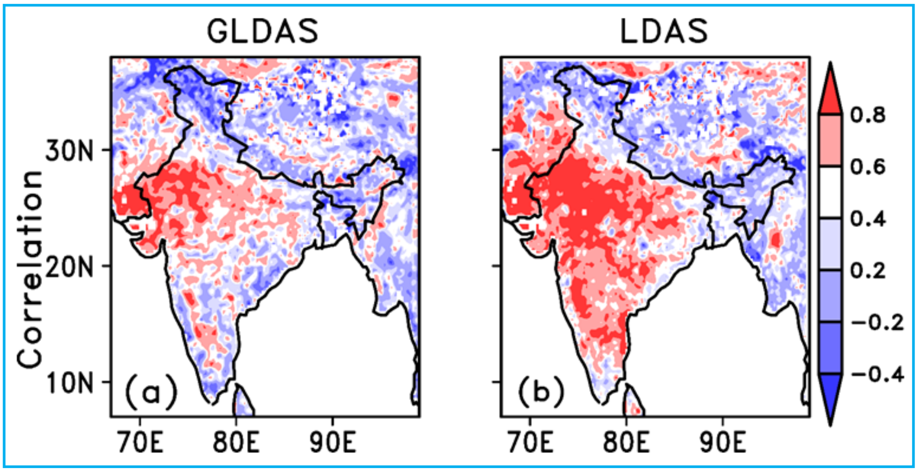


Fig. 5(a&b). Temporal correlation analysis of ESACCI soil moisture with GLDAS and LDAS. The temporal correlation of monsoon SM between (a) ESACCI and GLDAS for the period 2001-2014. (b) is same as (a) but for correlation between ESACCI and LDAS. The red color is confidence interval at 99%. The domain averaged correlation is 0.58 and 0.41 for LDAS and GLDAS respectively (Fig. from Nayak *et al*., 2018)

initiative (ESACCI; Dorigo *et al*., 2017) program as shown in Figs. 5(a&b).

5. Assimilation of Satellite SM product

The LDAS, outlined in the previous section, consists of uncoupled LSM forced with atmospheric surface parameters and estimates land surface conditions such as SM, ST and surface fluxes (Chen *et al*., 2007; Unnikrishnan *et al*., 2013; Osuri *et al*., 2017; Nayak *et al*., 2018, 2019). This LDAS based generation of land fields has been considered in different studies, for developing the indirect SM assimilation and needs observed atmospheric surface forcing at sub-daily (hourly or 3 hour) scale to drive the LSM. Over the Indian region, there is a general lack of atmospheric surface observations that provide forcing at sub-daily timescale. Moreover, the LSM, such as Noah used in the LDAS have uncertainties in simulating SM and ST due to the use of default, non-local soil properties (Nayak *et al*., 2019). In addition to the LDAS fields, there are satellite-derived products that emerge as another avenue for SM estimates. However, these products are limited by spatial coverage and satellite passage time. A hybrid approach that considers both satellite-derived SM and the LDAS fields are attractive. Such an approach facilitates satellite data assimilation within LSM products by considering their error characteristics and ultimately results in the development of a high-resolution product.

NASA LIS is another example of the satellite product and LDAS integration (LIS; Kumar *et al*., 2006). The LIS setup provides different sophisticated options for LSMs, including coupled Noah, Variable Infiltration Capacity (VIC), MOSAIC, CLM model etc. The LIS framework utilizes observations using the Kalman filter algorithm. A schematic of the LIS land surface modeling system is shown in Fig. 6. It uses sequential data assimilation (DA) algorithms that advance recursively with time by alternating between a model forecast phase and the assimilation update phase. The EnKF algorithm is a Bayesian filtering process that advances through alteration between an ensemble forecast step and a state variable update step. The model state advances using the nonlinear LSM prognostic, thermal and hydrological balance equations and the observations are used to update the simulated fields (Reichle *et al*., 2002). The updated land surface states are given as:

$$U_{i,j}^{t} = F_{i,j}^{t} + K\left(O_{i,j}^{t} - HF_{i,j}^{t}\right) \tag{3}$$

where, i is the grid number, j is the number of ensembles and $U_{i,j}^{t}$ is the updated state, $F_{i,j}^{t}$ is the forecasted state and $O_{i,j}^{t}$ is the observational state vectors. H is the observation operator and Kalman gain matrix which is denoted by K and is given as:

$$K = \frac{C_{\psi,\psi i}^{t}\; H_i^{tT}}{H_i^t C_{\psi,\psi i}^{t}\; H_i^{tT} + C_{\omega,\omega i}^{t}} \tag{4}$$

where, $C_{\psi,\psi i}^{t}$ and $C_{\omega,\omega i}^{t}$ are error variances for forecast and observation estimates, respectively.

In this study, an attempt has been made to assimilate SM estimates from the European Space Agency's Climate Change Initiative (ESACCI, Dorigo *et al*., 2017) using the ensemble Kalman filter algorithm in the LIS framework

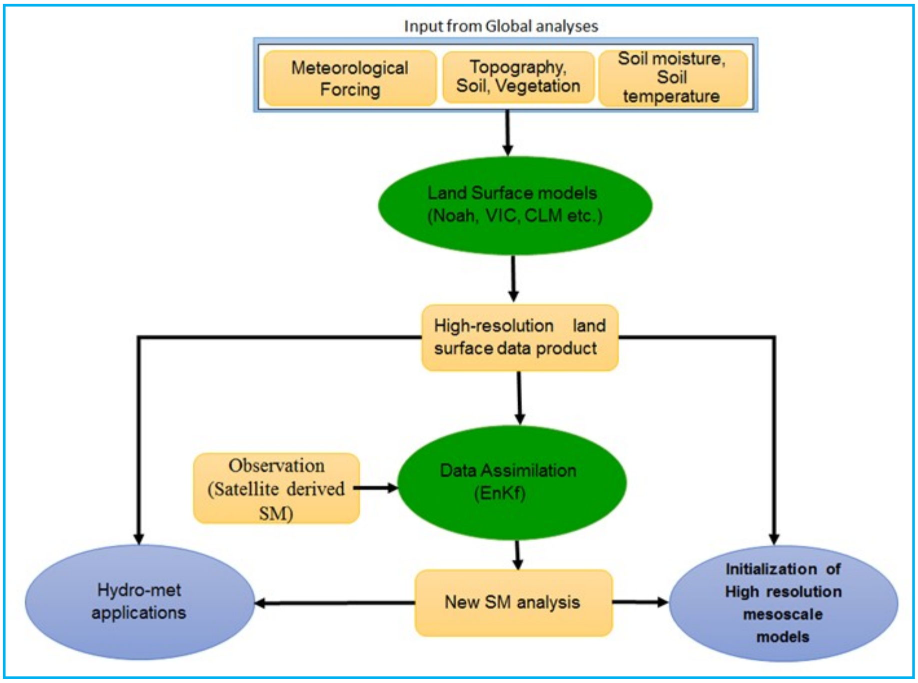
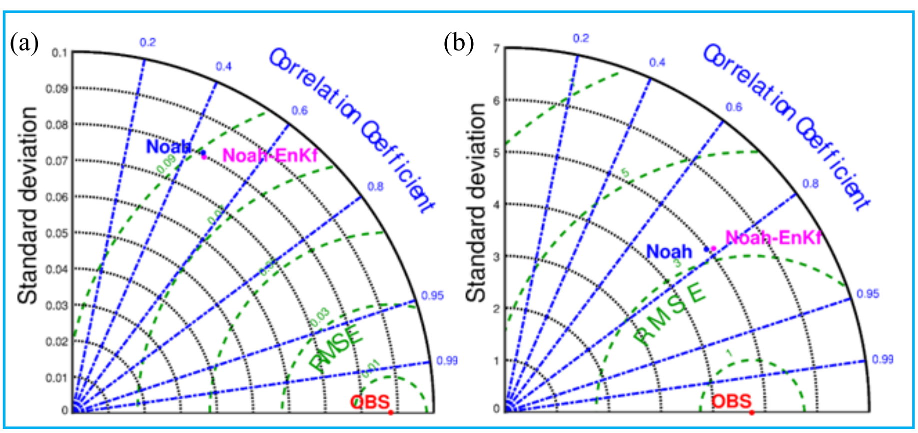


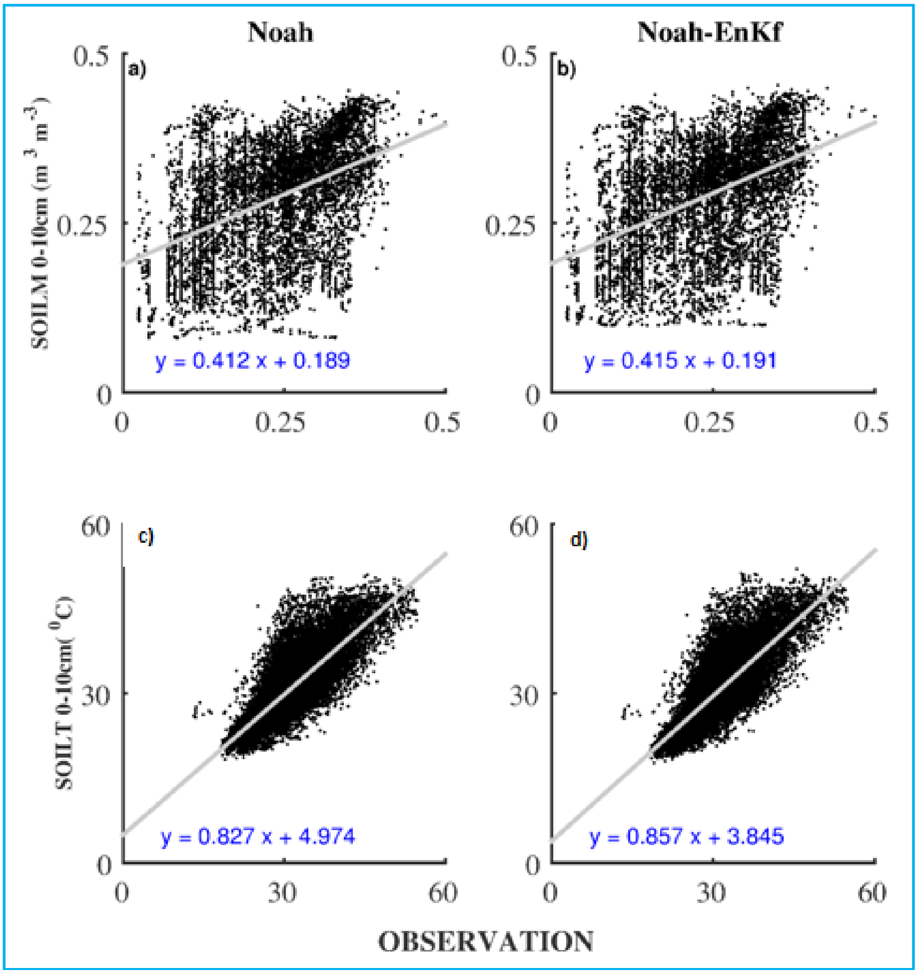
Fig. 6. Flowchart of satelite soil moisture assimilation using ensamble kalman filter algorithim. The green, yellow and light blue color represent the model integration/ assimilation, various data sources/products and application section respectivilly. The flowchart is based on NASA land information system (LIS) https://lis.gsfc.nasa.gov/software/lis)



Figs. 7(a&b). The mean error statistics including standard deviation, root mean square error and correlation coefficient of surface layer (0-10 cm) (a) soil moisture (m^3 m^{-3}) and (b) soil temperature (°C) from without (Noah) and with ESACCI soil moisture assimilation (Noah-EnKf) during monsoon season of 2011-2013

for the period 2000 to 2014. The Noah is chosen as the LSM for generating land surface state. The surface forcing parameters are provided from GDAS fields.

The analysis is done to drive the Noah LSM at 4 km spatial resolution. The assimilated SM product at 4 km spatial resolution and 3-hour temporal resolutions are validated with in-situ observations for the period 2011-2013. The land surface estimates from Noah run (without assimilation) and with ESACCI SM assimilation are compared against available (30) in-situ observations over India. Figs. 7(a&b) show a comparison between Noah and Noah-EnKf (assimilated SM) derived SM and ST products through the Taylor diagram (Taylor, 2001). The assimilated SM and ST product shows modest improvement over control (without assimilation). The scatter diagram for SM and ST from Noah and Noah-EnKf products [Figs. 8(a-d)] shows marginal improvement of assimilated SM and ST product (Noah-EnKf) than without assimilated (Noah) product.



Figs. 8(a-d). Comparison of ESACCI SM assimilation (Noah-EnKf) and free simulation of Noah against AWS observation during monsoon season of 2011-2013. First row represents scatter diagram of soil moisture from (a) Noah, (b) Noah-EnKf against ~30 AWS observations. (c&d) same as (a&b), but for soil temperature

6. Role of the land surface in weather and climate system

Land-atmosphere interaction plays a crucial role in modulating weather and climate system through the exchange of mass, energy and water (Avissar and Pielke, 1989; Pielke *et al*., 2011; Nayak and Mandal, 2012). As mentioned earlier, understanding and representation of these interactions have been a topic of active research in recent decades (Manabe, 1969; Henderson-Sellers *et al*., 1995; Chen and Dudhia, 2001; Ek *et al*., 2003; Nayak *et al*., 2019). Pertinent to the ISM, several studies have demonstrated the importance of land surface parameters on mesoscale convective events (Pal and Eltahir, 2001). The land surface heterogeneity due to variation in thermal and hydrological characteristics of soil can influence convective phenomena and affect atmospheric circulation. The heterogeneity in SM and surface roughness creates a mesoscale boundary that can impact mesoscale convergence, convective potential and, ultimately moisture instability as well as rainfall occurrence (Pielke, 2001).

The importance of SM heterogeneity in the development of deep-convection is well studied (Lanicci *et al*., 1987; Pielke and Zeng, 1989). A gradient in the SM fields creates differential surface heat fluxes, which cause land-sea breezes like lateral gradients in heating and winds leading to an increased potential for mesoscale convection (Pielke, 2001). The SM, especially at deeper layers, is a slow varying state variable that can help to improve sub-seasonal to seasonal atmospheric predictability (Dirmeyer *et al*., 2006). Through the surface moisture recycling process, the SM influences precipitation at a time scale ranging from seasonal to inter-annual scales (Dirmeyer *et al*., 2006).

6.1. *Role of the land surface on monsoon processes*

The impact of land surface processes on ISM is well established (Shukla and Mintz, 1982; Gadgil, 2003; Pielke *et al.*, 2003; Niyogi *et al.*, 2009; Takata *et al.*, 2009; Kishtawal *et al.*, 2010; Saha *et al.*, 2011). The land surface processes evolve at multiple spatiotemporal scales. For instance, aspects such as surface SM, ST and evapotranspiration typically evolve rapidly (order of hourly time scale) at the surface and slowly (order of days) in the deeper layers. As a result, their impact on ISM is manifested through various temporal scales that have the potential to influence short to long-range predictions. In terms of spatial feedbacks, studies note that an order of 10-30 km heterogeneity influences dynamical feedback on the mesoscale features such as convection and rainfall (Avissar, 1996). Indeed, smaller regional changes such as irrigation and urban features can also organize and affect the regional atmospheric processes over the IMR. Both these features, agriculture/ irrigation and cities have caused detectable impacts on the monsoon rainfall climatology in observational studies (Niyogi *et al.*, 2010; Kishtawal *et al.*, 2010).

The interannual variability of the ISM is governed by the atmospheric dynamics and underlying boundary forcing from land surface and ocean. The Eurasian snow cover plays an important role in determining the interannual variation of the summer monsoon (Peings and Douville, 2010). In broader terms, the interannual variation in ISM can be better explained with the incorporation of land surface parameters in multilinear regression models aimed to capture the variability (Ghosh *et al.*, 2018). The deeper land surface variables have a 'memory' on the atmosphere and similar to the oceanic SST, there is potential to assess this temporal feedback and modulation on the monsoonal circulations through land-atmosphere interaction. A better understanding of this memory feature from the land state can aid the prediction of seasonal and interannual variability. This aspect has been utilized in studies such as Niyogi *et al.* (2010); Lee *et al.* (2009); Saha *et al.* (2010), which indicate that February greenness and SM status over northern India can help to predict the July rainfall. Higher greenness fraction or moisture availability through irrigation could provide negative feedback *via* surface cooling, which could lead to the weakening of the surface low over the northwestern India/Punjab region. This surface feature *via* scale interaction could manifest a reduction in atmospheric jet and moisture transport over northwestern India, ultimately yielding reduced rainfall in July.

Despite the significance of the monsoon in agricultural and allied activities, it has not been adequately modeled (Webster *et al.*, 1998) and the role of land surface processes in the systems is still not well understood (Niyogi *et al.*, 2018). With diverse land surface characteristics, the surface feedback processes differ substantially in spatial scale. The sensitivity of SM on the Asian monsoon region differs in comparison with the African monsoon region (Douville *et al.*, 2001). The land surface feedback on the atmosphere is dominant over the climatic transition zones of the East Asian monsoon region, where the SM has a strong control over rainfall variability (Zhang *et al.*, 2011).

Several studies have also demonstrated the importance of land surface processes for seasonal prediction for the ISM (Shukla and Mintz, 1982; Singh *et al.*, 2007; Asharaf *et al.*, 2012; Unikrishnan *et al.*, 2017; Maurya *et al.*, 2017). The importance of land surface process in the pre-onset monsoon season was reported by Saha *et al.* (2011). This study revealed that pre-onset dry (wet) land state increases (decreases) the ISM rainfall. The importance of pre-monsoon SM on the ISM rainfall has also been demonstrated by Asharaf *et al.* (2012). Their study suggests that realistic SM simulation is necessary for the forecasting of the ISM. Similarly, Dutta *et al.* (2009) have shown that change in vegetation results in a significant change in rainfall and wind simulations.

At the short-range prediction scale, the importance of land surface processes on convective events, monsoon depressions (MDs), low-pressure systems, heavy rain events is also evidenced in a number of modeling and observational studies (Yoon and Chen, 2005; Kishtawal *et al.*, 2013). Baisya *et al.* (2017) found positive S - P feedback, especially for MDs. The SM feedback resulted in modified evapotranspiration and moisture flux convergence. The importance of SM initialization on monsoon modeling has been identified by Chang *et al.* (2009). Their study suggests that warmer and wetter land condition supports the intensification of the land-falling MDs over the IMR; while dry antecedent land conditions can dampen the MD intensity after the landfall. Kishtawal *et al.* (2013) extended this perspective of pre-landfall soil state and post-landfall MD impacts by reviewing the different MD clusters. The study resulted in a comprehensive climatological analysis of the positive relationship between wetter antecedent land conditions and the longer, sustained inland influence of the MDs. This understanding of the antecedent land state and MD rains is also noted in the model simulations. Vinodkumar *et al.* (2009) prescribed improved land surface processes through indirect SM and ST assimilation using a variety of datasets and showed improvements in MD simulations. The impact of high-resolution SM and ST initialization on simulation of convective weather events associated with monsoon is also demonstrated in Nayak *et al.* (2018).

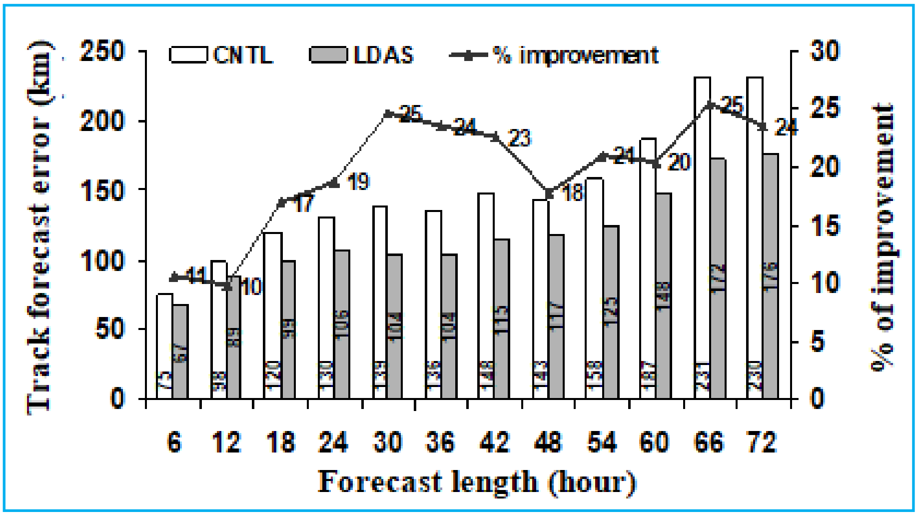
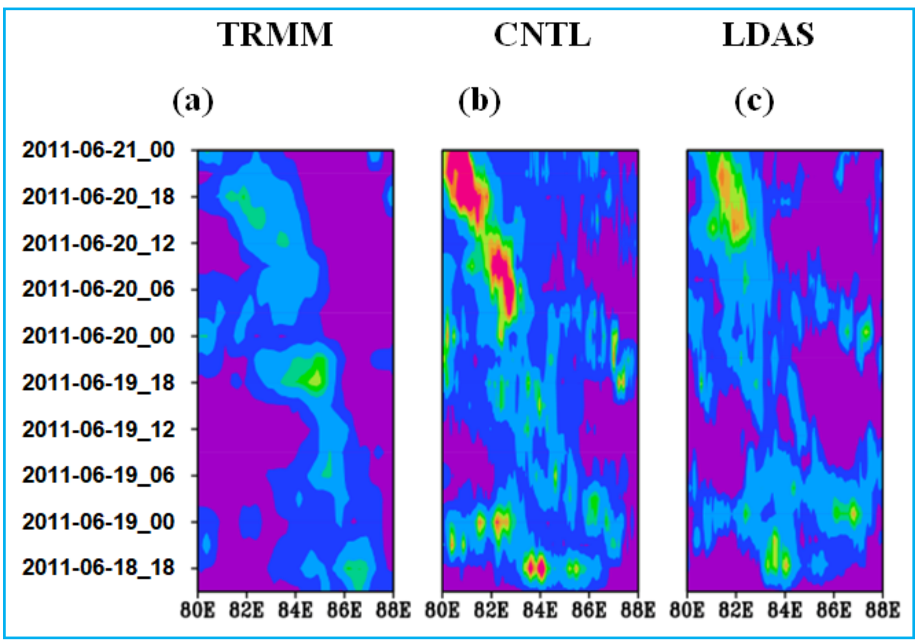


Fig. 9. The mean track forecast errors (km) with respect to observed track for CNTL and LDAS experiments. The line indicates the percentage improvement with LDAS experiment over CNTL run. The LDAS experiments have enhanced SM, ST initial conditions as compared to CNTL and are otherwise identical in the model setup



Figs. 10(a-c). Time-longitude cross-section of 3 hour rain rate averaged over a latitudinal box of 23°-25° N for (a) TRMM (b) CNTL and (c) LDAS for a typical landfalling MD case (18 July, 2011). Figure is reproduced from Nayak *et al*., 2018)

Building on the success noted in prior reports, in this study, further assessment is made regarding the impact of accurate representation of land surface characteristics (such as SM and ST) on simulation of heavy rainfall associated with intense convective activities such as inland MDs for eight recent cases. The LDAS derived high-resolution SM and ST profiles at 4 km resolution is used as a land initial condition in the WRF-ARW NWP model, which was run at the same grid resolution. For the eight MD cases, two sets of different numerical experiments were performed by initializing SM and ST from climatology and referred to as CNTL and from the 4 km LDAS derived SM and ST referred to as LDAS experiments. Besides the SM and ST, all other model configuration was maintained identical. The surface meteorological parameters such as 2 m temperature, relative humidity, rainfall and surface turbulent flux simulations were analyzed and when compared against available observations, the results show consistent improvements in LDAS experiments. The improved model fields ultimately resulted in an improved MD track in the LDAS as compared to the CNTL. The mean track errors from both the experiments are shown in Fig. 9. For the 24-, 48- and 72-hour simulation period, the errors in the default CNTL are about 130, 143 and 230 km, respectively. When the model is run with improved SM and ST fields for initialization, these errors reduce to 96, 107 and 176 km for the same period resulting in an improvement of about 25%.

In a related study, Nayak *et al*. (2018) reviewed the impact of LDAS initialization on model simulated rainfall for MD. The experiments were carried out with similar configurations except with and without LDAS high-resolution SM and ST initialization for a typical MD case (18 July, 2011) over the Indian region. The 3-hour rain rate simulation from the study is shown in Figs. 10(a-c), as a time-longitude cross-section averaged over a latitudinal box of 23°-25° N. The rain-rate is overestimated in the CNTL experiment when compared to TRMM rain rate estimates. The LDAS experiment showed an improved rainfall and realistic amount and spatiotemporal distribution as compared to the CNTL experiment. The improvement in the model fields is chiefly due to the realistic initialization of SM and ST data products in the WRF-ARW model.

7. Summary and future scope

This review seeks to provide a primer on the evolution and state of land surface processes and its significance over the Indian monsoon region. The review, by design, is slanted towards the operational modeling environment. It seeks to provide the perspective regarding challenges or opportunities available in terms of using land surface process studies in improving monsoon rainfall predictions over the Indian region. As a summary and future directions needed in the coming decades, the following is highlighted.

(*i*) The land surface processes play an essential role in the ISM energetics and rainfall at varied time scales on the short, medium and long-range forecast. Indeed, land surface feedbacks also interact and influence the inter-annual and inter-seasonal variability of ISM notably. These features are highlighted in many studies that build off both observational analyses, as well as numerical modeling experiments and is considered a robust conclusion.

(*ii*) Studies indicate with notable consistency that enhanced the representation of land surface processes in NWP models either though detailed land surface parameterization schemes and/or improved land surface data assimilation results in improved simulation of ISM at multiple scales. It is interesting to highlight that the impact of enhanced land surface representation on the monsoon rains is likely best noted and consistently found in the literature for short term, heavy rain and thunderstorm simulations. The results are also generally broadly consistent and positive in terms of the improvements seen when detailed land surface representation is made within regional model simulations over the ISM domain. On the other hand, the direct association between enhanced land surface representation and improved monsoon simulation is less consistently noted in the global modeling studies. Why this inconsistency emerges is not clear from the available literature and a perspective is presented here. The land surface effect on monsoon rains is likely manifested as feedback of enhanced coupling between the land and the boundary layer, which impacts the mesoscale energetics and in turn, can modulate convection and other activities that are linked to rainfall simulations. These features are perhaps best represented in current NWP models that run at higher resolutions (finer grid spacings) for mesoscale and regional model simulations. In addition to the role of model resolution, it is likely that global models have other dynamical features such as (a) parameterized cloud/ convection with limited mesoscale land heterogeneity influence, (b) detailed aerosol physics, which is often more dynamically represented in global models as compared to NWP models, (c) larger ocean domain as compared to the regional models and (d) relatively coarse vertical grid structure, which may lead to reduced coupling between the land surface grids and the global atmosphere. Nonetheless, there is strong evidence that enhancing land surface representation is one effective way of improving models' ability to simulate rainfall over the IMR.

(*iii*) The analysis of land surface impacts on monsoon and the performance of models for simulating monsoon processes, both need land surface datasets such as soil moisture and soil temperature (SM and ST). While these data are challenging to develop due to constraints in developing representative measurements, especially for soil moisture fields, the availability and credibility of the state-of-art LDAS system for the IMR provide a good avenue for developing these fields. The availability of multi-decadal, high-resolution SM and ST data products over IMR, under the Monsoon Mission project (Nayak *et al*., 2018), yields the opportunity for realistic land fields to be used as initialization of land surface models for NWP studies. The improved land surface initialization has yielded notable improvements in simulating the track and rainfall associated with thunderstorms as well as MDs over India. The impact of high-resolution SM and ST initialization on seasonal simulation of ISM remains a topic of future focus for the Indian region.

(*iv*) Even though LDAS products have shown to have a positive impact on the model performance, the direct assimilation of satellite SM fields such as from ESACCI in Noah LSM has demonstrated a limited impact. Such limited improvement highlights the need for a more rigorous understanding of the manner in which SM, ST fields should be integrated into coupled models and their effect on the monsoon energetics and rainfall processes. It is likely that assimilating deeper (root zone) soil fields would have a more notable impact on large-scale feedback rather than the surface fields that are typically available from the remotely sensed products. Indeed, an important future study topic would be to develop enhanced LDAS/ root zone fields using surface satellite products and assess the impact this has on monsoon simulations.

(*v*) In addition to the soil fields, such as SM and ST from LDAS, the seasonal forecast of ISM is constrained due to the use of static vegetation characteristics in the NWP/LDAS models. The incorporation of dynamic vegetation in the seasonal forecast of ISM remains a future scope. This includes particular consideration of dynamic crop models as agricultural landscapes form a major part of the monsoon region. These landscapes show rapid changes in their greenness fraction, foliage density, height, water use, landscape management, albedo and transpiration impact, which affects surface energy balance and hence, the boundary layer processes. The consideration of dynamical vegetation models, therefore, holds great potential and needs to be considered in future studies.

(*vi*) Urbanization across India and much of the monsoon region is another landscape change that is dynamically underway. Explicit representation of urban features in land surface models is an emerging area and holds great potential for the ISM region, especially as issues such as urban flooding and urban heat island/heat stress are on the rise. Future studies related to the urban land surface processes and representation of urban processes on ISM both as a climate as well as NWP aspect is expected to be of high importance (Gupta *et al*., 2018).

(*vii*) With growing computational power, increasing access to satellite data resources and societal demand from the meteorological community to provide high-resolution, localized predictions especially for high impact and extreme events, the role of land surface processes is expected to be increasingly prominent in coming years. Land surface processes and models continue to emerge as an interface between meteorology, air quality, floods, heat stress, hydrometeorology and interseasonal changes across the Indian monsoon domain.

(*viii*) There is a need for a concerted effort to develop regionally and locally representative land products, conduct land model calibration-validation studies and develop coupled model evaluation studies that capture land processes across the ISM. Such a coordinated effort focused around operationalizing land surface products within forecast modeling suite holds great promise for improved predictions and highlights a call for sustained research focus and translation of research findings into operational centers such as at the India Meteorological Department to operationally integrate LDAS and detailed land models in the operational forecast models. Such an endeavor will undoubtedly lead to an improved ability to predict monsoon rainfall characteristics and vagaries, especially under extremes, using coupled modeling systems.

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