MAUSAM, **74**, 2 (April, 2023), 345-360

MAUSAM

DOI : https://doi.org/10.54302/mausam.v74i2.6199
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 515 : 551.553.21 : 551.577.5

Role of land surface processes on Indian summer monsoon rainfall : Understanding and impact assessment

U. C. MOHANTY*, **, HARA PRASAD NAYAK*, ***, M. R. MOHANTY*, P. SINHA*,
RAGHU NADIMPALLI[#] and K. K. OSURI[##]

**School of Earth Ocean and Climate Sciences, Indian Institute of Technology Bhubaneswar – 752 050, India*

***Centre for Climate Smart Agriculture, Siksha 'O' Anusandhan Deemed to be University, Odisha, India*

****Department of Geography, University of California Los Angeles, USA-90095*

[#]*India Meteorological Department, MoES, New Delhi – 110 003, India*

[##]*Department of Earth and Atmospheric Sciences, National Institute of Technology Rourkela, India*

e mail : ucmohanty@iitbbs.ac.in; ucmohanty@gmail.com

सार – भारतीय ग्रीष्मकालीन मॉनसून एक सिनोप्टिक-स्केल वायुमंडलीय परिसंचरण प्रणाली है जो महाद्वीपों और उष्णकटिबंधीय महासागरों दोनों कीपरिसीमा सेप्रभावित होती है। महासागरों के विपरीत, भू सतह की विशेषताओं और उससे संबंधित प्रतिक्रियाओं में विषमताओं के कारण भू सतह प्रक्रियाएं जटिल हैं, जिससे NWP मॉडल में भू सतह का सटीक प्रतिनिधित्व बाधित होता है। इस प्रकार, भूमि-वायुमंडल की परस्पर क्रिया को समझना विशेष रूप से भारतीय ग्रीष्मकालीन मॉनसूनके ऋतु के दौरान अंतर्निहित उष्ण और नम सतह के कारण अति महत्वपूर्ण हो जाता है जो वाष्पोत्सर्जन के प्रति अत्यधिक संवेदनशील होते हैं, जिससे ऋतु के दौरान भूमि के वातावरण युग्मन को बढ़ावा मिलता है। सतह माप की कमी के कारण सतह विषमता और विविधता का प्रतिनिधित्व सीमित है जिससे भू सतह विश्लेषण के विकास की आवश्यकता का पता चलता है। वर्तमान अध्ययन का प्रमुख उद्देश्य त्रिस्तरीय है, पहला, मॉनसूनी वर्षा की घटनाओं से जुड़ी भू सतह की प्रक्रियाओं को समझना, दूसरा, भारत में एक स्टेट-ऑफ-आर्ट उच्च-विभेदन भूसतह डेटा तैयार करना और अंत में, अनुकारी मॉनसूनी वर्षा की घटनाओं पर उच्च विभेदन भू सतह आरंभीकरण के प्रभाव का मूल्यांकन। यह अध्ययन भारतीय ग्रीष्मकालीन मॉनसून से जुड़ी बेहतर पूर्वानुमान प्रणाली विकसित करने से संबंधित हैं।

ABSTRACT. Indian Summer Monsoon is a synoptic-scale atmospheric circulation system manifested by the boundary forcing from both continents and tropical oceans. Unlike oceans, the land surface processes are complex in nature due to the heterogeneities in land surface characteristics and its associated feedbacks, thereby constraining the accurate representation of the land surface in NWP models. Thus, understanding the land-atmosphere interaction becomes increasingly crucial especially during the Indian summer monsoon season due to the underlying warm and moist surface layer that are highly sensitive to the evapotranspiration, thereby fueling land atmosphere coupling during the season. The representation of surface heterogeneity and variability are constrained due to lack of surface measurements which necessitate development of land surface analysis. The major aim of the present study is three-fold; firstly, understanding land surfaces processes associated with the monsoonal rainfall events, secondly, preparation of a state-of-art high-resolution land surface data over India and finally, impact assessment of high-resolution land surface initialization on simulation monsoonal rainfall events. This study has implications for developing improved prediction system associated with the Indian Summer Monsoon.

Key words – Land-atmosphere interaction, HRLDAS, Soil moisture, Soil temperature.

1. Introduction

The earth's surface exchanges energy, moisture, momentum and gases with overlying atmosphere (Baldocchi *et al*., 2001; Pielke 2001). The surface of earth controls partitioning of the energy received at surface by converting the energy into turbulent surface fluxes and thereby modulating the atmospheric boundary layer stability, convection and precipitation (Nayak *et al*., 2022; Maity *et al*., 2022). Through these exchanges, the land surface influences and gets influenced by the atmosphere and thereby modifying the weather and climate system. There are several pathways in which land surface influences atmosphere. The evapotranspiration is one of such important pathways that connects surface to the atmosphere and is central to energy, water and carbon cycle. The changes in vegetation alter the surface albedo and thereby control the net radiative flux and convective clouds which in turn affects rainfall (Charney, 1975; Charney *et al*., 1977). Further, the land surface processes can alter the biogeochemical cycle through biomass decomposition in the land, thereby impacting the monsoon climate. Besides, there are dynamical feedbacks through which land surface influences the atmospheric circulation and modulates moisture transport from remote locations (Ashraf *et al*., 2012).

Soil moisture is an important climatic parameter that has several primary applications, such as in real-time drought/flood monitoring (Svoboda *et al*., 2002), agribusiness, river flow forecasts, land surface hydrology process studies (Bhattacharya and Mandal, 2015; Nayak *et al*., 2018, Osuri *et al*., 2020). Soil moisture initialization plays a key role in the mesoscale simulation of atmospheric events in land-atmosphere coupled numerical models (Osuri *et al*., 2017; Nayak *et al*., 2018). The soil moisture recycling plays an important role in the local scale convective activities over land particularly in monsoon season. The appropriate information on soil moisture has manifold utilities, particularly for the crop models and water management decisions. The soil moisture also contributes to atmospheric predictability at seasonal timescales. For instance, soil moisture affects summer precipitation predictability owing to the longer land memory and stronger soil moisture-precipitation coupling (Koster *et al*., 2004; Dirmeyer, 2009). The slowly varying soil moisture “remembers” past and present precipitation anomalies and the resulting soil moisture anomalies influences precipitation occurrence through its feedback to the atmosphere. This cycle of moisture leads to persistence of soil moisture and precipitation anomalies. Numerous studies have divulged the issue of how soil moisture anomalies impact on subsequent climate conditions (Rind, 1982; Shukla and Minz, 1982; Paegle *et al*., 1996; Bosilovich and Sun, 1999; Pal and Eltahir, 2001; Georgescu *et al*., 2003; Kim and Wang, 2007). Most of these studies support positive feedback between soil moisture and precipitation, indicating wetter (drier) than normal soil tends to promote (suppress) precipitation. The possible pathways for the land feedback include local moisture recycling (Bosilovich and Chern, 2006) as well as changes in moisture convergence from remote sources (Oglesby and Erickson, 1989).

Besides, soil temperature also affects the surface heat flux at various timescales. Because of heat conduction in soils, soil heat anomalies of daily or weekly timescales in shallow layers near the surface are released to the atmosphere before being distributed to the deeper layers (Hillel, 1980). Only persistent long-term (such as inter-annual and decadal-scale) anomalies in surface heat budget can propagate to deep soil layers and affect temperature variations in those layers (Lachenbruch and Marshall, 1986; Beltrami and Harris, 2001; Beltrami, 2002). The above studies have emphasized the importance of soil moisture and soil temperature modulating the weather and climate systems. Also, high-resolution soil moisture and soil temperature heterogeneity have crucial role on weather and climate predictability. However, the high-resolution soil moisture and soil temperature representation requires a dense network of land surface observations and such observations are usually limited particularly over the Indian region. It also challenging to operate a dense network of soil moisture and soil temperature observations over a wide region over the Indian land mass. Thus, creating soil moisture and soil temperature field using the Land Data Assimilations System (LDAS) is one of the most suitable ways of addressing this issue (Chen *et al*., 2007; Nayak *et al*., 2018; Lim *et al*., 2012; Rodell *et al*., 2004). One of the important objectives of this study is to develop and validate high-resolution soil moisture and soil temperature field over India.

The Indian Summer Monsoon (ISM) is one of the most dominant weather phenomena that contribute ~80% of annual total rainfall over India (Mohanty *et al*., 2019; Mohanty *et al*., 2023a). The ISM is primarily developed due to the boundary forcing from the Ocean. For instance, the basin-wide tropical sea surface temperature (SST) plays major role for the development of ISM. Besides these oceans forcing, the land surface processes considerably influence the ISM rainfall. The land surface influence is particularly important for Indian monsoon region and the region is identified as one of the important “hotspots” for land-atmosphere coupling in the world (Koster *et al*., 2004). The land-atmospheric coupling is important, particularly in ISM season owing to abundance of moisture and energy. The surface evaporation depends on the soil moisture content; however, excess soil moisture over a critical value does not enhance surface evapotranspiration notably. Similarly, evapotranspiration ceases when the soil moisture lies below the wilting point (Budyko, 1974; Seneviratne *et al*., 2010). Therefore, the soil moisture between wilting point and critical value are important for land atmosphere coupling. Thus, soil moisture becomes a strong function of evapotranspiration in summer monsoon season due to availability of surface moisture and energy.

Besides the surface evapotranspiration, rainfall is also influenced by the dynamical feedback of land surface

TABLE 1

WRF model configuration used in the land surface sensitivity experiments

Dynamics	Non-hydrostatic
Domain 1 Domain 2	-3° S - 35° N and 55° E - 100° E (Domain 1) 9° N - 26.8° N and 75° E - 93.9° E (Domain 2)
Number of domains	2
Horizontal grid distance	12 and 4 km
Map Projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Vertical co-ordinate	Terrain-following hydrostatic-pressure co-ordinate
Time Integration	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Initial & boundary conditions	3-dimensional real data (FNL : 1° × 1°)
Microphysics	WSM 6 class scheme
Land Surface Scheme (LSM)	NOAH, Thermal diffusion
Surface layer parameterization	Meller Yamada Janić (MYJ scheme)
Convection schemes	Explicit (No-Cumulus scheme)
PBL parameterization	Mellor-Yamada- Janić (Eta)scheme

TABLE 2

Heavy rainfall cases and model simulation length considered in the study

Rainfall cases	Model initialization time	Model integration period
Case-1	2013-06-14:00	(72 hour)
Case-2	2013-08-20:00	(72 hour)
Case-3	2015-06-20:00	(48 hour)
Case-4	2018-08-07:00	(48 hour)

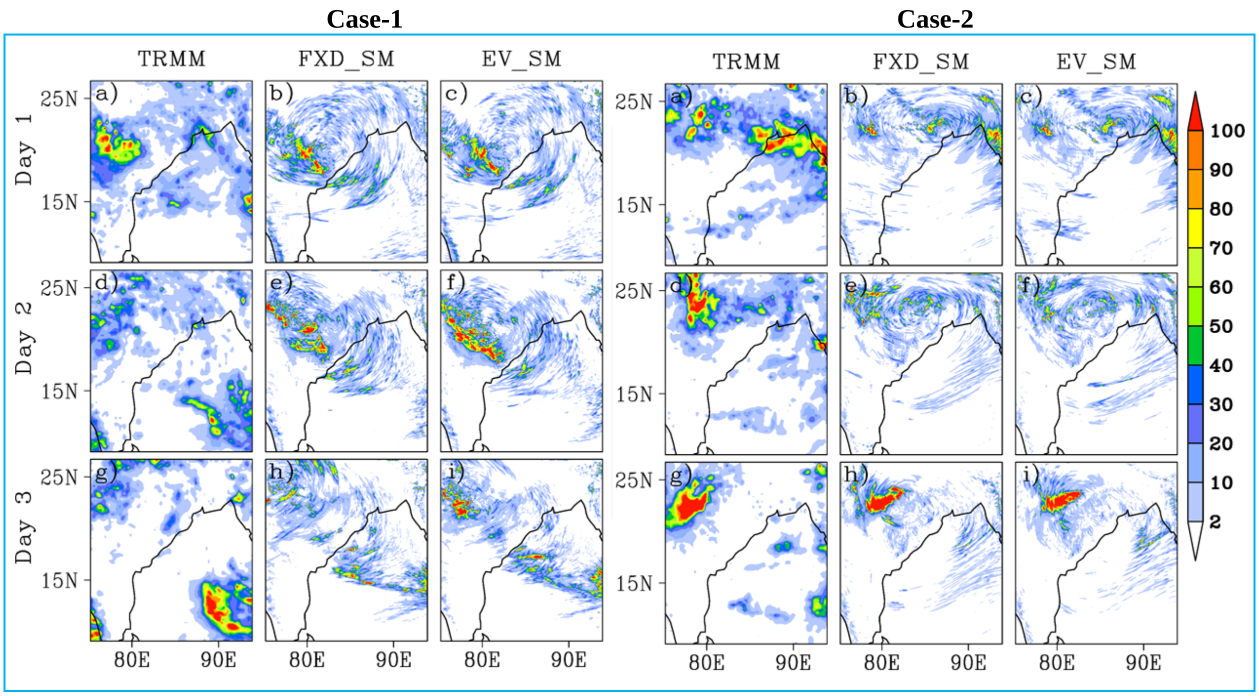
processes (Taylor *et al*., 2012). Regional climate modeling studies have shown that the surface moisture plays a significant role in precipitation distribution (Maurya *et al*., 2021; Ankur *et al*., 2021) and its feedback helps in supplementing the moisture from ocean surface associated with ISM (Devanand *et al*., 2018). The land cover change due to agricultural activities in monsoon impacts the moisture cycle in dynamical models. The increase in paddy cultivation also led to an increase in September rainfall over India (Devanand *et al*., 2019). Intense irrigation could cause decrease in precipitation over the north western India. Baisya *et al*. (2017) found strong positive soil moisture-precipitation feedback associated with Indian summer monsoon depressions. Besides monsoon depressions and mesoscale convective activities, extreme rainfall events during the monsoon season were also largely controlled by the land atmosphere feedback process (Mohanty *et al*., 2023b).

The present study addresses following three major aspects: (*i*) Understanding land surfaces processes associated with the monsoonal rainfall events, (*ii*) preparation of the state-of-art high-resolution land surface data over India, (*iii*) Impact assessment of high-resolution land surface initialization on the simulation of monsoon rainfall events.

2. Understanding land surfaces processes associated with the monsoonal rainfall events

In this section, we study the influence of land surface processes on monsoonal rainfall events associated with the Indian summer monsoon over India. In order to understand the land surface influence, land surface sensitivity experiments are conducted using the state-of-the-art mesoscale model WRF-ARW (Advanced and Research WRF) coupled with the land surface schemes: Noah and the five-layer thermal diffusion scheme. The Noah and thermal diffusion schemes use different approach for surfaces oil moisture estimations. The Noah uses prognostic equation for soil temperature and soil moisture and utilizes more sophisticated vegetation and surface hydrology (Chen *et al*., 1996; Chen and Dudhia, 2001; Ek *et al*., 2003; Mahrt and Pan, 1984; Koren *et al*., 1999), whereas the thermal diffusion scheme does not have prognostic equation for the soil moisture and utilizes a seasonal soil moisture as a function of land use (Dudhia, 1996). As a result, the soil moisture evolves realistically with time in Noah, whereas the thermal diffusion scheme uses fixed soil moisture during the monsoon season. Following the experimental design, Noah scheme (hereafter referred as EV_SM experiment) and thermal diffusion scheme (referred as FXD_SM experiment) are used to understand the land surface sensitivity associated with monsoonal rainfall events. These land surface schemes are used to simulate four monsoonal rainfall events over the Indian region. A brief description of the model configuration and the monsoonal rainfall events studied are presented in Table 1.

The model integration is carried out over two nested domains with horizontal resolution 12 and 4 km, respectively. The first domain covers the Indian monsoon domain (Table 1) and the second domain covers the Bay of Bengal and central and eastern India, so that large-scale and local influence could accommodate in the model simulation. The monsoonal rainfall events are selected in order to represent the contrasting surface conditions: two cases in June and two cases in August (peak monsoon month). The underlying surface conditions are quite distinct during these



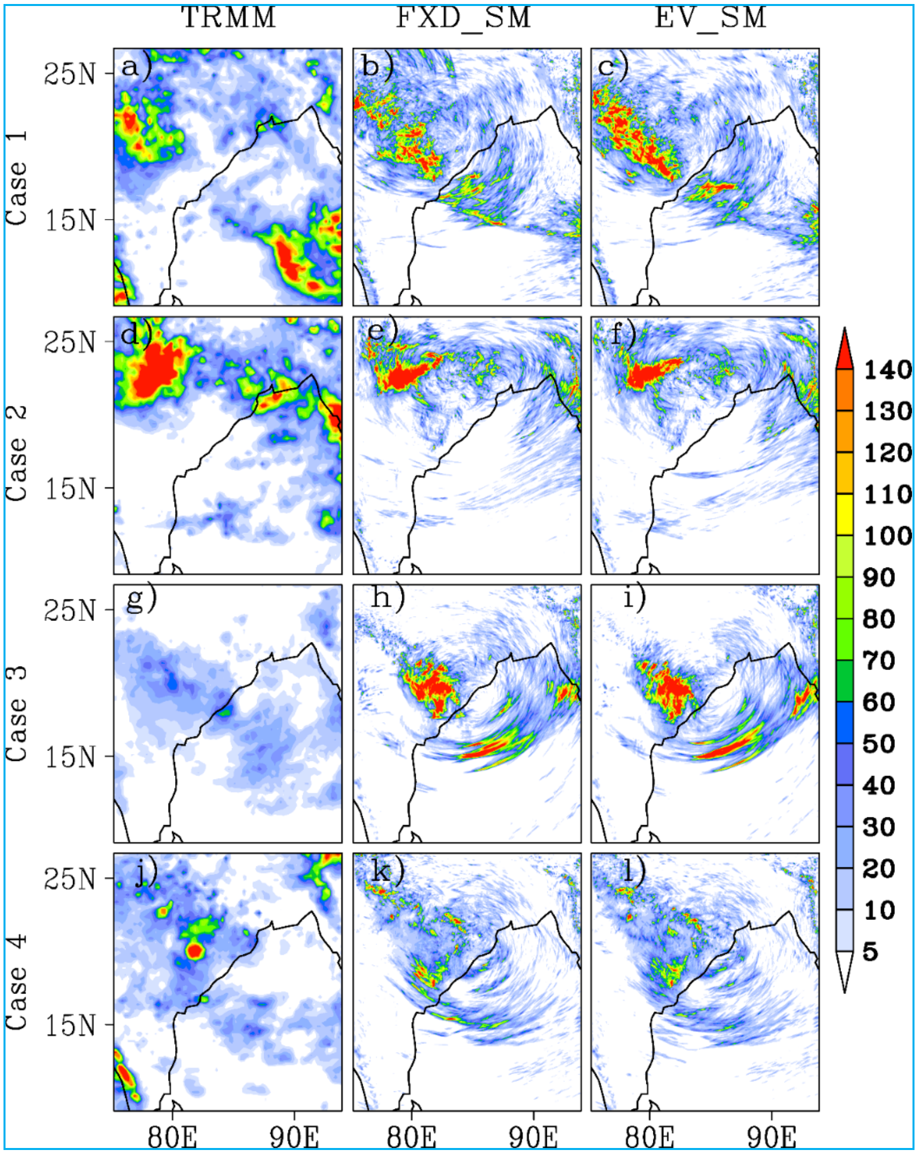
Figs. 1(a-i). Daily (day-1) accumulated rainfall (mm) from (a) TRMM (b) FXD_SM, (c) EV_SM experiments of case-1. (d-f) and (g-i) are same as (a-c) but for day-2 and day-3, respectively. The right panel represents same as left panel but for case-2

two months. A set of numerical experiments (Table 2) are conducted to study the impact of land surface processes on monsoonal rainfall events. Rainfall and moisture transport/budgets are analyzed to assess the impact of soil moisture on the water cycle in the WRF model.

2.1. *Rainfall*

Figs. 1(a-i) show the day-1, day-2 and day-3 rainfall simulation for two monsoonal rainfall cases (on 14th June, 2013 and 20th August, 2013) and those are compared with the Tropical Rainfall Measuring Mission rainfall estimate. Our analysis indicates the monsoonal rainfall events are sensitive to land surface processes. The sensitivity is dominant for cases in June as compared to cases in August. The model simulations show discrepancies in the rainfall simulation among the sensitive experiments in June, particularly in day-2 and day-3 simulations. Contrary to this, the rainfall simulation is found to be similar in August. Such sensitivity is likely attributed to underlying soil moisture condition for respective rainfall cases. It is also noticed that the location of heavy rainfall is not well simulated in day-1 as seen in both case-1 and case-2.

The accumulated rainfall from the all the land surface sensitivity experiments is compared with TRMM rainfall as shown in Figs. 2(a-i). In general, the rainfall spatial patterns are found to be similar in both EV_SM and FXD_SM experiments, but the rainfall magnitude differs. The model simulated rainfall does not show any systematic bias in both sensitivity experiments. For instance, both sensitive experiments underestimate the rainfall in the case-2 (20th August, 2013) and overestimate the rainfall in case-3 (20th June, 2015 case). In case-1, the TRMM rainfall ranges between 100 - 130 mm over central India. Though the model simulation could reproduce rainfall amount reasonably, the spatial distribution is poorly simulated, particularly in the FXD_SM simulation. Moreover, rainfall simulation is overestimated in southeast direction as compared to TRMM rainfall in both experiments. For the 20th June, 2015 case (case-3), the TRMM rainfall ranges between 10-60 mm over the eastern India, whereas the model overestimates by 30-50 mm over the same region in both the sensitive experiments. The rainfall sensitivity to the land surface process is least in case-4. Overall, the rainfall simulation is distinct in the rainfall cases in June compared to cases in August as seen in both sensitive experiments. Such sensitivity may be linked with underlying soil moisture condition. Note that soil is generally drier and heterogeneous in June as compared to August which may affect the rainfall simulation. On the other hand, the soil moisture is nearly saturated in August. The soil moisture sensitivity is likely less over the saturated surface (Seneviratne *et al.*, 2010). The discrepancies in the findings as observed for the drier and wetter conditions indicates that the soil moisture does play an important role

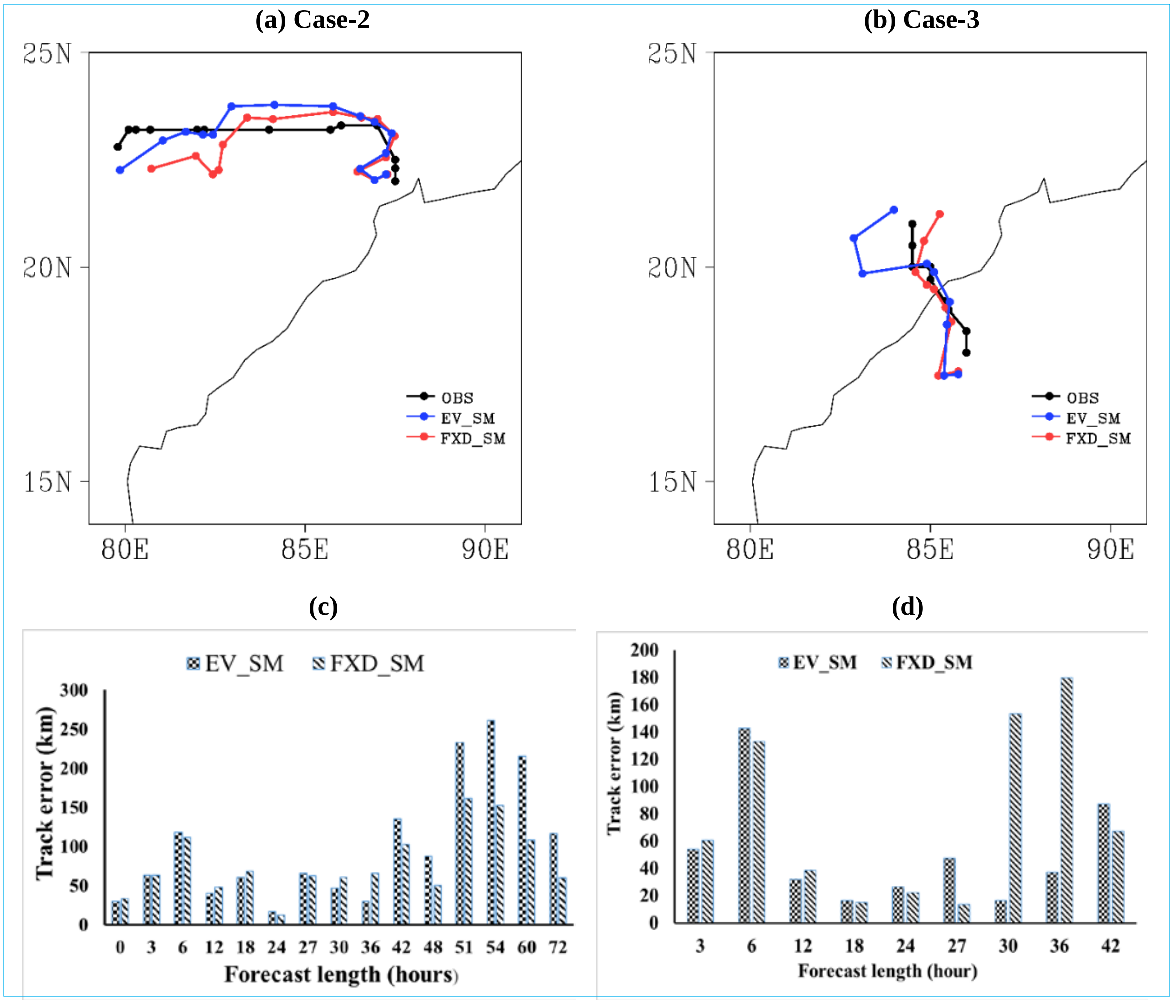


Figs. 2(a-i). Accumulated rainfall (mm) from (a) TRMM (b) FXD_SM, (c) EV_SM experiments for case-1. (d-f), (g-i) and (j-l) are same as (a-c) but for case-2, case- 3 and case-4, respectively

in the land-atmosphere interaction and moisture recycling during the monsoon seasons. The study indicates land surface processes are an important component of monsoon rainfall events and therefore realistic land surface representation may be useful for the improvement in monsoonal rainfall simulation.

2.2. *Track of MDs*

In this section, we show land surface sensitivity to monsoon depression track simulation. Among the four heavy rainfall cases, two cases (case-2 and case-3) marked as monsoon depression by India Meteorological Department, India and the same cases are considered for the analysis. The model simulated tracks from these two cases (case-2 and case-3) along with the IMD best-estimated track are shown in Figs. 3(a&b). The 850 hPa streamlines are used to determine the center of the monsoon depression. The result shows overall track predictions are reasonably good in both cases. Among the two monsoon depression cases, the case-2 is a land depression whereas case-3 is an inland moving BoB depression. Figs. 3(c&d) show the track error statistic (in km) with the simulation length of the monsoon depression forcase-2 and case-3, respectively. In case-2, the track forecast error is ~100 km until the 48 hour (day-2) and the error has increased in day-3 forecast with maximum track error ~ 260 km in the 54th hour. The FXD_SM has higher



Figs. 3(a-d). Model simulated track from EV_SM and FXD_SM experiments along with IMD best fit estimates for monsoon depression cases (a) Case-2 and (b) Case-3. The lower panel represents the track error statistics (km) for the monsoon depression cases, (c) Case-2 and (d) Case-3

error, particularly in day-3 simulation. In contrast, EV_SM experiment has higher error in case-3 and the track error is ~180 km at 30-36th hour. The analyses indicate that monsoon depression track simulation is sensitive to land surface parameterization, thus, the land-atmospheric interaction in the model is one important factor to predict the track of depression and its associated rainfall.

2.3. *Atmospheric Water Budget*

The atmospheric water budget is governed by precipitation, evapotranspiration and moisture convergence/divergence (Yoon and Huang, 2012) and can be expressed as:

$$\frac{\partial W}{\partial t} + \nabla.\vec{Q} = E - P \qquad (1)$$

where, W is the atmospheric precipitable water,

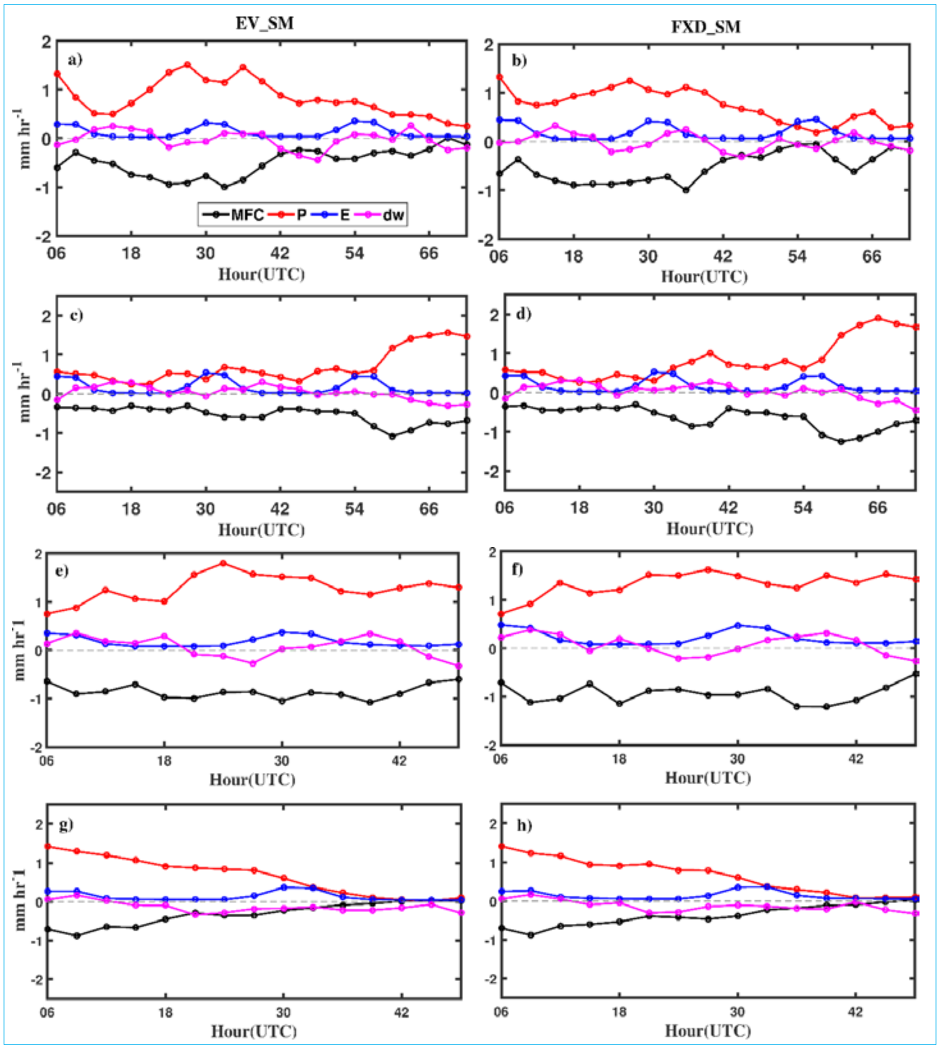
$\partial W/\partial t$ is the storage term denoted as dw,

($\nabla.\vec{Q}$) is known as Moisture Flux Convergence denoted as "MFC",

E is the surface evaporation and

P is the precipitation.

The moisture budget terms are computed over 5° × 5° domain averaged over the storm center. For long-term average, local rate of change of specific humidity is negligible and therefore, MFC is balanced by precipitation and evapotranspiration. The atmospheric moisture budget provides the partitioning of moisture sources and sink over the land surface. Figs. 4(a-h) represents 3-hourly time series of model simulated moisture budget terms



Figs. 4(a-h). 3-hourly time series of model simulated moisture budget terms such as storage term (dw), moisture flux convergence (MFC), precipitation (P) and Evaporation (E) of (a) Noah (b) TD experiment from case 1. (c-d), (e-f) and (g-h) are same as (a-b) but for case 2, case 3 and case 4 respectively

such as storage term (dw), moisture flux convergence (MFC), precipitation (P) and evaporation (E) of both EV_SM, FXD_SM experiments for all four rainfall cases. For simplicity, all the terms are computed in mm $hour^{-1}$. It is seen that the moisture budget term differs among the sensitive (EV_SM and FXD_SM) experiments. The precipitation (P) perceives the maximum variability followed by MFC in all the experiments. The precipitation temporal variability followed the MFC variability indicating the MFC has strong control on rainfall. Wei *et al*. (2016) suggested that MFC has a strong control on the rainfall amount and frequency which corroborates with the present study. The magnitude of E is found to be small in comparison with MFC. There are diurnal variations of E in all the cases. The magnitude of E is higher in FXD_SM experiment than EV_SM experiment, particularly for cases in June than in August [(Figs. 4(a-h)]. Note that the rain rate is higher in EV_SM experiment. The magnitude of dw is found be small in all the cases. The analysis indicates MFC plays a major role in supplying the moisture into the system followed by E and the findings is consistent with prior studies (Yoon and Huang, 2012; Wei *et al.*, 2016). Soil moisture is the major source of moisture over the land surface which contributes to the moisture flux convergence. This signifies the importance of soil moisture in a dynamical model.

The sensitivity studies of the two land surface schemes in simulating the rainfall during monsoon show that the soil moisture plays a vital role in simulating precipitation. Also, the moisture fluxes over land, especially during the dry monsoon days are quite sensitive to the rainfall. The land atmosphere feedback process transports the moisture from the soil into the atmosphere through evaporation and moisture flux transport. Hence, land surface models can have a better impact on improving the skill of dynamical models in simulating precipitation. Real time computation of land surface processes and interactive land-atmosphere dynamics needs to be represented in a dynamical model. For extracting the best of land surface models, observational data is necessary for initializing the land surface processes.

In an extensive study, the representation of soil moisture from five different sources in the regional climate model is studied for the simulation of Indian summer monsoon seasonal rainfall (Maurya *et al*., 2021). They used reanalysis fields of soil moisture and found that the representation of soil moisture differs from source to source. However, it is interesting to note that they found positive relationship between rainfall/evapotranspiration and soil moisture and the role of SM tend to be positive during monsoon season, while, a negative relation is observed between soil moisture and sensible heat flux.

3. High-resolution land surface data over Indian region

The previous section demonstrates the role of soil moisture modulating the land surface process feedback on monsoonal rainfall events. Thus, the representation of land surface parameters and its spatiotemporal variability is important for land atmosphere interaction. The land surface representation becomes challenging, particularly over the Indian region due to heterogeneity in surface conditions such as land use and land cover, vegetation, topography and soil moisture distribution. The high-resolution land surface representation requires land surface observations. However, the land surface observations are too sparse to represent the surface heterogeneity over the Indian monsoon region. Limitations in the land surface observation constraints the representation of spatiotemporal variability and the associated predictability of weather and climate models (Robock *et al*., 2000). Further, a dense network of surface observations is challenging to operate beyond a watershed. The alternative approach to address this deficiency is to create high-resolution surface conditions by using a land data assimilation system (LDAS) consisting of uncoupled LSM forced by near surface atmospheric observations (Chen and Zhang, 2009). The LDAS derived land surface products have been evaluated over different regions of the world (Cosgrove *et al*., 2003; Mitchell *et al*., 2004; Rodell *et al*., 2004; Lim *et al*., 2012; Nayak *et al*., 2018; Nayak *et al*., 2019) and is widely used. The performance of LDAS is highly dependent on the surface characteristic such as soil, vegetation and land use

TABLE 3

Data used for the generation of the LDAS

Atmospheric forcing	CFSR hourly data at (0.2044° X 0.2045°) resolution (T2, specific humidity, PSFC, U and V wind)	Bilinear interpolation
Radiation	GLDAS 3 hourly SWRAD and LWRAD radiation at 0.25°resolution	Linear interpolation to hourly and bilinear in space
Precipitation	TRMM hourly precipitation at 0.25°resolution	Mass conservation interpolation
Soil texture	16-category 5-min USGS soil texture	No interpolation from WRF grid to LDAS grid
Land use	19-category 30 s resolution NRSC land use	No interpolation from WRF grid to LDAS grid
vegetation	30 s resolution USGS green vegetation fraction	No interpolation from WRF grid to LDAS grid

information. In addition, soil parameters have considerable influence on the LDAS derived land surface conditions and therefore need to be carefully provided to the LDAS systems (Nayak *et al*., 2019). Here we discuss the present state of land surface data generation and validation over the IMR.

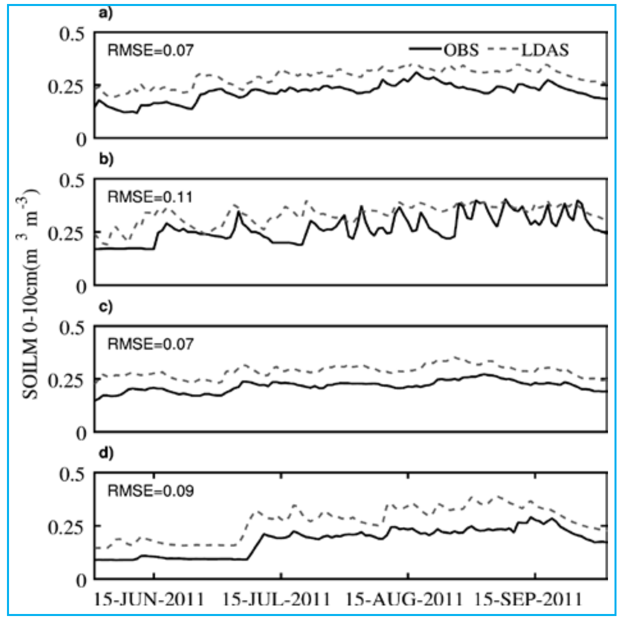
The LDAS requires high spatio-temporal resolution observations to drive the LSM and the quality of the land surface estimation depends on the quality of the forcings (Nayak *et al*., 2018; Vergopolan *et al*., 2022). Although, there is considerable surface observation available over the Indian monsoon region, those observations are not adequate for driving high-resolution LDAS. An alternative approach is to use a best available reanalysis product to drive the LDAS. Therefore, reanalysis products from Modern Era Retrospective-analysis for Research and Applications (MERRA; Rienecker *et al*., 2011), MERRA Version-2 (MERRA2; Bosilovich *et al*., 2017), National Centres for Environmental Prediction - Climate Forecast System Reanalysis (NCEP-CFSR; Saha *et al*., 2010), European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim; Dee *et al*., 2011) and Global Land Data Assimilation System (GLDAS; Rodell *et al*., 2004) are validated (by Nayak *et al*., 2018) against *in situ* observations over India region. Their study suggested that the T2, surface pressure from NCEP-CFSR and downward short wave and longwave radiation from the GLDAS exhibits least error and have better accuracy. Therefore, the said data could be a better source for the development of LDAS system. The input forcing fields and soil and vegetations information used for the development of the LDAS are presented in Table 3.

The temperature and specific humidity at 2 m, surface pressure, zonal and meridional wind are used from the CFSR data. The short wave and long wave radiations are used from the Global Land Data Assimilation System (GLDAS) at 0.25° resolution. The data from the CFSR and GLDAS are then bi-linearly interpolated to 4 km and provided the LDAS over Indian region. The LDAS system is initially integrated for the period 2001-2014 with time integration of 15 minutes. The LDAS estimates soil moisture, soil temperature at surface and sub-surface soil layers (0-10, 10-40, 40-100 and 100-200 cm) along the surface sensible, latent and ground heat fluxes. The validation of the LDAS soil moisture and soil temperature against AWS station observations available over India are discussed further.

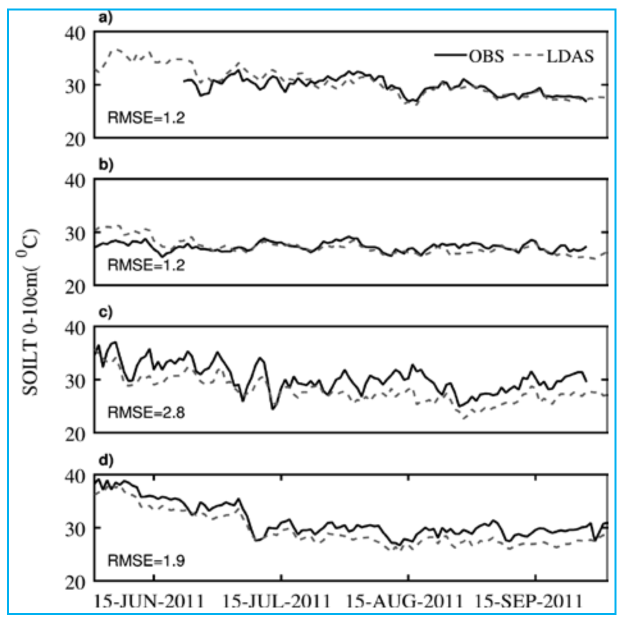
Figs. 5(a-d) depicts validation of surface layer soil moisture against *in situ* observations over different regions of India such as North, South, East and West (Nayak *et al*., 2018). The results show that the LDAS soil moisture agrees with observations. The LDAS soil moisture has root mean square error ~0.07,0.11,0.07 and 0.09 m^3m^{-3} for north, east, south and west regions, respectively. It is also seen that the LDAS soil moisture has consistent positive bias in all the regions. The bias in LDAS is likely attributed to the climatological soil parameters used in the LDAS (Nayak *et al*., 2019). The biases may also be attributed to the uncertainty in TRMM rainfall estimates (Huffman *et al*., 2007). Similarly, the daily time series of surface layer soil temperature validated with AWS station observation over four different regions of India such as North, South, East and West [Figs. 6(a-d)]. The root mean square error between LDAS and observed soil temperature is 1.2, 1.2, 2.8 and 1.9 (°C) for North, East, South and West, respectively. Note that the soil temperature validation over south is constraint due to limited number of observations and the available observations are mostly over the complex terrain regions. Usually, the reanalysis data have higher uncertainty over the complex terrains and uncertainty in reanalysis forcing leads to higher biases in the LDAS soil temperature.

However, this argument is not validated in the present analysis and therefore could not be confirmed. The error in other three regions (North, East and West) is reasonable and the data could be further improved.

The LDAS soil moisture and soil temperature at four soil layers are further expanded for generating long-term climatological data for the period 1981-2017. These climatological data utilized IMD daily gridded rainfall, surface meteorological condition from NCEP-CFSR and radiation from MERRA2 for driving the LDAS. The LDAS also used the local land use data from NRSC. Fig. 7 represents monthly climatology of the volumetric soil moisture (m^3 m^{-3}), soil temperature (K) at surface soil layer and rainfall over India. The figure shows that the monthly soil moisture climatology primarily followed the



Figs. 5(a-d). Validation of top layer volumetric soil moisture content against observation during JJAS season, 2011 over India. The root mean squared errors are highlighted over the top left corner of each panel. (Fig. from Nayak *et al*., 2018)



Figs. 6(a-d). Verification of soil temperature against observation during JJAS season, 2011 over India. The daily time series of soil temperature (°C) at 0-10 cm of observed and LDAS for (a) north, (b) east, (c) south and (d) west. (*Source* from Nayak *et al*., 2018)

monthly rainfall climatology. However, spatial distribution of soil moisture differs from rainfall pattern in some months. For instance, the soil moisture pattern does not follow rainfall in September over the central India. This is likely due to soil moisture memory from preceding

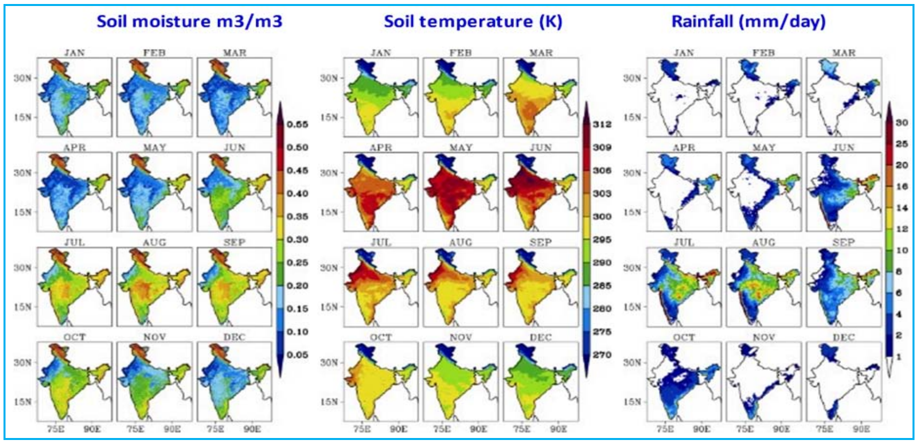


Fig. 7. Monthly climatology of the soil moisture (m^3 m^{-3}), soil temperature (K) and rainfall (mm/day) over the period 1981-2017. The soil moisture and soil temperature are computed from the LDAS whereas the rainfall as observed in the IMD dataset

June and July. The soil memory also depends on soil texture, vegetation and topography. For instance, finer soil texture of a clay soil exhibits longer memory than the coarser sandy soil. The soil temperature climatology shows monthly variation over India.

The soil moisture, soil temperature and rainfall exhibit spatio-temporal variations and the variations are more complex for soil moisture and rainfall, particularly in monsoon season. In monsoon season, higher (~0.4 m^3/m^3) soil moisture is noticed over north east and central India region than the peninsular and northwest India which is anticipated with the monsoonal rainfall distribution. Moreover, the central India soil moisture is notably higher (~ 0.20-0.25 m^3/m^3) than other regions during the dry period (January-May) when the rainfall is ~ 1 mm/day. The comparative higher soil moisture over central India is likely due to moisture retention properties of the clay soil prevalent over this region (Nayak *et al.*, 2018, 2019). The March and April are the dry months, (soil moisture ~0.05-0.2 m^3/m^3) and the northwest is the driest region (soil moisture ~0.05-0.1 m^3/m^3) compared to remaining parts of India. Note that western Himalaya region exhibits higher soil moisture (>0.5 m^3/m^3) and lower soil temperature seen in all the months. This region is covered by ice/snow resulting higher soil moisture over the region. The rainfall distribution over this region is characterized with the western disturbances during November to March and monsoonal rain during June - September every year. Unlike other parts of India, this region experiences higher rainfall (6-8 mm/day) in March than in all other months.

The soil temperature decays with progress of monsoonal rainfall while the northwest region remains the warmest in June. As the soil reaches to its saturation in July and August, the soil temperature decays with the monsoonal rain. However, the south peninsular India, mostly leeward side of the Western Ghats receives less rainfall during summer monsoon (JJAS) leading to warmer soil temperature. This region reaches to its near saturation during northeast monsoon season. In general, the soil temperature is the warmest in May (~306-312 K) except the northwest region where soil temperature attains its maximum in June (> 312 K). The coolest surface soil temperature over Indian region is seen in December (~290-300 K). There are clear latitudinal variations of soil temperature in all the months. Interestingly, rise in soil temperature propagates from south to north following the northward movement of solar position during December to May. It is also seen that latitudinal variation of soil temperature follows the monsoon precipitation during JJAS. During October, the soil temperature is mostly homogeneous (~295-300 K) over the Indian region. The region experiences least rainfall in January and highest rainfall in July and August months. The central India receives highest amount of rainfall in August (~20 mm/day) followed by the July month. Thus, with such a complex land surface with distinctive soil properties over different times of the year, it is indeed very important to incorporate integrated land surface models in numerical models with accurate land surface data to improve the predictive skill of any model aimed at forecasting the weather and the climate of the Indian sub-continent.

4. Impact of soil moisture initialization on simulation of intense convective activities

The validity of high-resolution soil moisture and soil temperature dataset is demonstrated in the previous section. The said data set provides a good source of land surface product over Indian region and have utility on

TABLE 4

Monsoon depression cases and the time period of simulation

Cases	Monsoon depression	Forecast length
Case-1	2007-06-29_00	36 hours
Case-2	2007-08-05_00	66 hours
Case-3	2007-06-21_00	48 hours
Case-4	2007-07-04_00	96 hours
Case-5	2008-06-16_00	30 hours
Case-6	2008-09-16_18	66 hours
Case-7	2009-07-20_00	30 hours
Case-8	2011-06-18_12	96 hours

various sectors such as weather and climate forecast, agriculture, hydrology and water resources (Nayak *et al.*, 2018; Maity *et al.*, 2022; Liao *et al.*, 2016; Liu *et al.*, 2015; Yang *et al.*, 2016). In this section, we investigate the impact of high-resolution soil moisture and soil temperature initialization on the simulation of monsoon depression over India. The premise of this study comes out of the framework that realistic land surface representations impact the surface boundary layer processes and there by affect convection and hence numerical model predictions. This study aims to understand the impact of accurate representation of land surface characteristics (such as soil moisture and soil temperature) on the movement and rainfall amount simulation associated with monsoon depressions.

Eight Monsoon depression cases are selected during the period from 2007 to 2011 over the Indian monsoon region and the details of these case studies are provided in Table 4. Numerical experiments are conducted to simulate monsoon depression using mesoscale model (ARW). The LDAS derived soil moisture and soil temperature fields are initialized in ARW model to study the impact of realistic land surface presentation on simulation monsoon depression over the IMR.

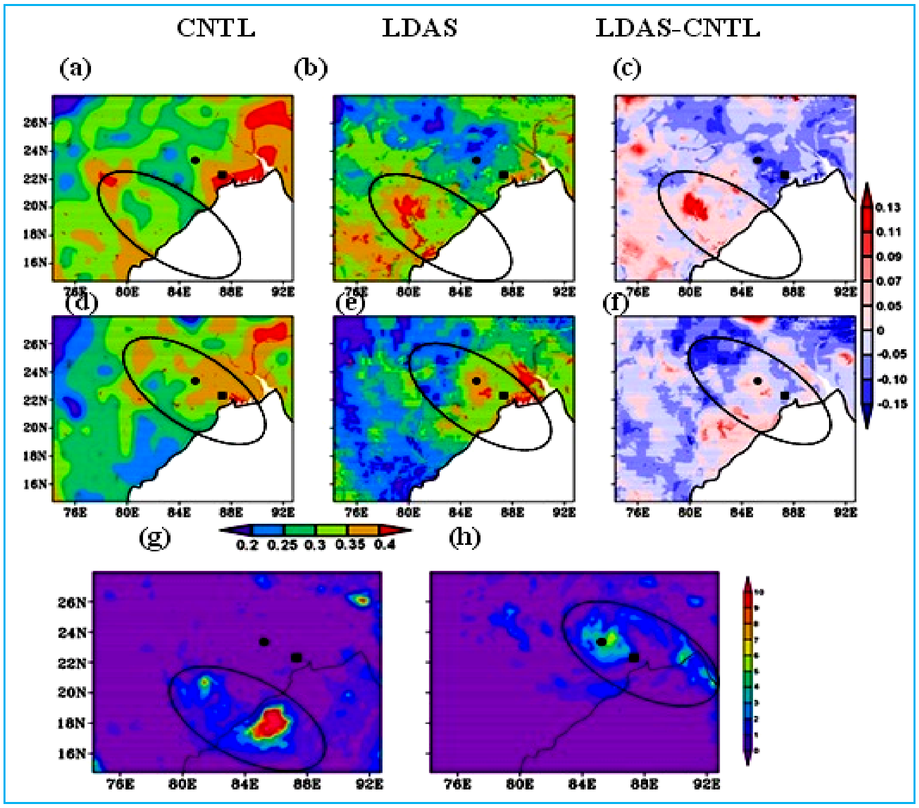
Two sets of numerical experiments are carried out for each monsoon depression cases using a single domain of 4 km horizontal resolution. The model uses Meller Yamada Janjic (MYJ) planetary boundary layer (PBL) scheme (Janjić, 2001), Monin-Obukhov Janjic surface-layer option (Janić, 2001), RRTM longwave (Mlawer *et al.*, 1997), Dudhia shortwave radiation (Dudhia, 1989) and WSM6 microphysics (Hong *et al.*, 2010) with explicit convection. The first experiment uses the initial and boundary conditions from National Centre for Environmental Prediction (NCEP) FiNaL analyses (FNL) in 6-hour interval referred as CNTL experiment. In the second experiment, the soil moisture and soil temperature profiles at 4 depths and top layer canopy water content of (CNTL) FNL analysis is replaced with those of LDAS and is referred as LDAS experiment. The other land surface characteristics such as vegetation, soil type, land use and land type etc., are obtained from United States Geological Survey (USGS) data and kept the same for both the experiments.

4.1. *Results*

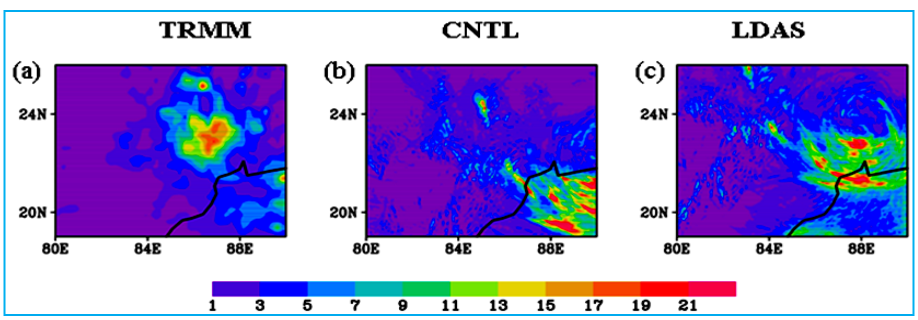
The volumetric soil moisture (m^3 m^{-3}) from CNTL and the LDAS experiment is compared at the initial time to demonstrate the credibility of the LDAS soil moisture. Figs. 8(a-h) show the CNTL and LDAS soil moisture at surface layer and their difference (LDAS-CNTL) for two representative MDs such as case-1 and case-8. The CNTL shows smoother soil moisture field, whereas the LDAS soil moisture exhibits strong horizontal heterogeneity. Klink (1992) demonstrated that land surface discontinuities at smaller scales are important for better atmospheric circulations. Note that the soil texture from USGS is used in both experiments.

In case-1, TRMM rainfall estimate shows the precipitation occurrence (~ 20 mm) 24-hour prior to storm initiation highlighted in the elliptic region [Fig. 8(g)]. This rainfall region is in good coherence with higher soil moisture values in the LDAS experiment [Fig. 8(b)]. Fig. 8(g) shows, no rainfall over the northern parts of the domain (above 22° N). The observed rainfall variation with latitude is well captured in the LDAS experiment, *i.e.*, northern parts of the domain have lower soil moisture compared to the region in the elliptic. However, this is completely reverse in the CNTL experiment [Fig. 8(a)] inferring that the region with no rainfall has more soil moisture (northern parts of domain) whereas less soil moisture seen in the elliptical region. This inference clearly seen in difference plot [Fig. 8(c)] suggesting LDAS captured the realistic horizontal soil moisture structure following the observed rainfall. Similarly, case-8 shows LDAS based initial soil moisture field is in good agreement with the previous day rainfall [Fig. 8(h)]. The rainfall region is highlighted by an ellipse shown in figure 8h. However, the previous-day-rainfall signature is missed in CNTL soil moisture. Similar to case-1, CNTL shows over estimation of soil moisture over the northern parts of the domain (in case-8).

This shows that climatological (FNL) soil moisture has a positive bias over that region which is reasonably improved in the LDAS. Because of unavailability of observations, this discussion is drawn in connection with rainfall. However, the minor discrepancy between observed rain and LDAS soil moisture is noticed because the soil moisture field is not only determined by the rainfall alone rather depends on other surface forcing fields.



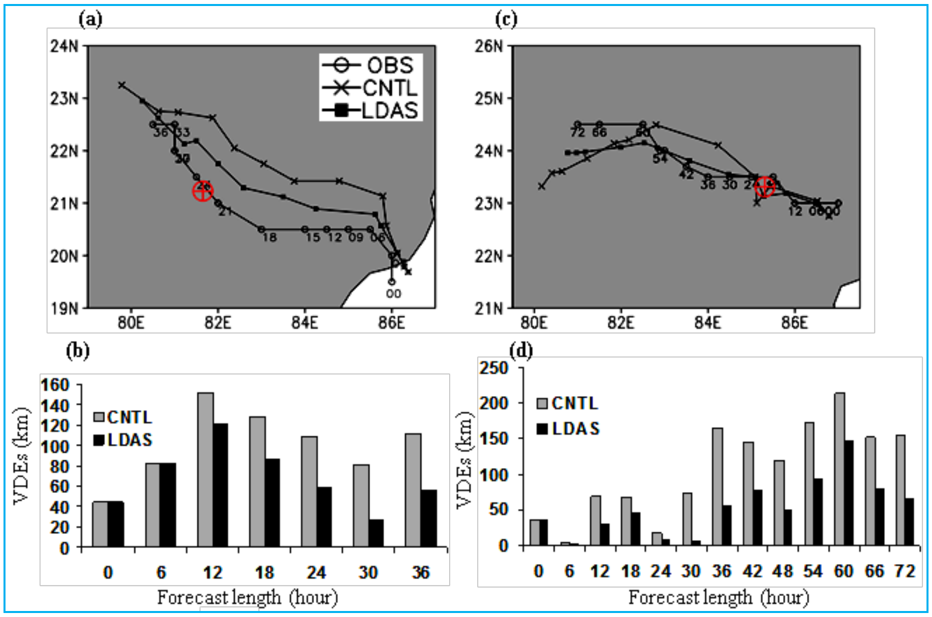
Figs. 8(a-h). Initial surface layer SM for case-1 (a) CNTL (b) LDAS and (c) LDAS-CNTL. (d-f) are same as (a-c) but for case-8. (g) and (h) represents 24-hour accumulated rainfall (mm) prior to storm initiation from TRMM corresponding to case-1 and case-8, respectively



Figs. 9(a-c). Accumulated 48-hour rainfall for the monsoon depression case-3 over Odisha

The model simulated rainfall from both experiments is compared with the TRMM rainfall to demonstrate the impact of soil moisture and soil temperature initialization on rainfall simulation associated with monsoon depression. Figs. 9(a-c) depicts 48-hour accumulated rainfall from both CNTL and LDAS experiment compared with the TRMM rainfall for the case-3. The result clearly indicates that the LDAS experiment improves the rainfall simulation over the CNTL experiments.

The rainfall is underestimated in CNTL experiment over West Bengal and adjoining region which is improved with the LDAS soil moisture and soil temperature initialization. The TRMM data shows rainfall ~ 7-17 mm over the land whereas the CNTL could reproduce only 1-5 mm rainfall. The LDAS experiment improves the simulation reproducing ~5-15 mm rainfall over the land region. Moreover, the spatial distribution of rainfall simulation is also improved in the LDAS. The rainfall improvement in the LDAS experiment may be attributed to land-atmosphere moisture feedback. It is evident that rainfall simulation associated with monsoon depression is sensitive to land surface initialization and the inference is consistent with the findings in the section 2.



Figs. 10(a-d). Monsoon depression track and associated track error due to the control and LDAS experiments for the case-1 and case-8

Model simulated tracks and their track forecast errors for CNTL and LDAS experiments are shown for the MDs cases (case-1 and case-8) in Figs. 10(a-d). The overall track prediction by LDAS is better as compared to CNTL. There is no change in the initial position of both the experiments and is deviated by about 50 km from the observed position. In case-1 [Fig. 10(a)], both experiments simulate the tracks almost similar over the BoB. Once the system crosses the land, each experiment showed notable change in track prediction. The LDAS experiment shows improvement in track simulation owing to high-resolution inhomogeneous land surface (soil moisture and soil temperature) initialization. The CNTL simulated system moved northward having more track errors with respect to the observed track. The track errors from CNTL run are about 60, 98, 55, 140, 170 and 95 km for 6-36 hours forecast in 6-hour interval. Whereas the same errors in case of LDAS run are about 48, 49, 45, 75, 30 and 80 km, respectively**.** Further, the LDAS predicted better intensity evolution in case-1. In the observation, the system weakened after crossing the land. Unlike observation, CNTL showed intensification of the system even after the landfall in terms of both minimum sea level pressure (MSLP) and higher wind speeds. However, though LDAS simulated system is relative weak, it followed the observed pattern and the error is less as compared to CNTL. Similarly, the case-8 also shows consistent improvement in track forecast and yielded less track forecast error. Note that the case-8 is a land depression case persisted for 72-hour as shown in Figs. 10(a-d). The improvement in the track simulation is evident both in land depression as well as depression over ocean associated with monsoon demonstrating the impact of LDAS soil moisture and soil temperature initialization on monsoon depression simulation.

5. Summary and future prospects

The land surface processes become increasingly important during the ISM due to underlying warm and moist surface condition over IMR and the surface heterogeneity induces manifold effects making the land surface processes more complex. The aim of the study is: (*i*) understanding land surfaces processes associated with the monsoonal rainfall events, (*ii*) preparation of the state-of-art high-resolution land surface data over India and (*iii*) impact assessment of high-resolution land surface initialization on simulation monsoon rainfall. The summary and future directions of the study are as follows:

(*i*) The monsoonal heavy rainfall events are sensitive to land surface parameterization and the sensitivity varies notably with underlying surface condition. The sensitivity is higher during the monsoon onset months compared to the monsoon active phase in August. It is likely that the warmer surface temperature favors surface feedback leading to precipitation modification. The water budget analysis indicates that the moisture flux convergence is the primary source of moisture associated the monsoonal heavy rainfall event over India. The surface evaporation also considerably contributes to the monsoon rainfall. The analysis also demonstrates that the track of the monsoon depression is sensitive to land surface processes and the sensitivity is notable in day-2 and day-3 of the simulation.

(*ii*) High-resolution long term (1981-2017) soil moisture and soil temperature data at surface and subsurface soil layers provides a good source of land surface dataset over India. The validation of the data set with AWS and satellite estimates indicates the quality of the LDAS soil moisture and soil temperature data. But its performance varies in different regions such as in east, west, north and south. The dataset could capture the diurnal, seasonal and interannual variability (Nayak *et al*., 2018). The data set also exhibits bias in soil moisture and soil temperature, suggesting for further improvements. The biases are attributed to the use of climatological soil parameters such as soil field capacity, soil porosity, thermal conductivity etc., which is considered as a limitation of LDAS. Further, utilization of high-resolution solar radiation and sub daily rainfall observation may likely improve soil moisture and soil temperature estimations.

(*iii*) The impacts of LDAS soil moisture and soil temperature initialization on mesoscale simulation of monsoon depression are assessed over India monsoon region. The result indicates that the soil moisture and soil temperature initialization improve the rainfall and track simulation of monsoon depression. It may also be noted that the improvement in rainfall simulation is not consistent for all the MD cases and needs further investigation and the same remains as future scope of the study.

(*iv*)The role of high-resolution land surface representation on seasonal simulation of ISM is yet to be investigated and the same remains future scope of the study. Further, the NWP models use static vegetation in the seasonal ISM forecast. The use of dynamic vegetation models such as dynamic crop model is likely to improve the seasonal simulation of ISM. This is important particularly for Indian region as the agricultural landscape contributes a major part of the ISM region. This landscape rapidly changes during the ISM leading to change in green fraction, LAI, surface albedo, plant transpiration etc. and thereby modifies the surface energy balance and hence influences the boundary layer processes. Therefore, the dynamic vegetation models have potential to improve the land surface feedback and need to be considered in the future seasonal ISM forecast studies.

Note that conclusions (*i*) and (*iii*) are tentative as these inferences are drawn from a limited number of case studies. Further work will be needed to ascertain these conclusions.

Acknowledgements

The authors acknowledge assistance from Dr. Rajesh Kumar Maurya.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Ankur, K., Nadimpalli, R. and Osuri, K. K., 2021, "Evaluation of Regional Land Surface Conditions Developed Using The High-Resolution Land Data Assimilation System (HRLDAS) with Satellite and Global Analyses Over India", *Pure and Applied Geophysics*, **178**, 4, 1405-1424.

Asharaf, S., Dobler, A. and Ahrens, B., 2012, "Soil moisture-precipitation feedback processes in the Indian summer monsoon season", *J. Hydrometeorol*., **13**, 1461-1474.

Baisya, H., Pattnaik, S. and Rajesh, P. V., 2017, "Land surface-precipitation feedback analysis for a landfalling monsoon depression in the Indian region", *Journal of Advances in Modeling Earth Systems*, **9**, 1, 712-726.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S. and Wofsy, S., 2001, "FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour and energy flux densities", *Bulletin of the American Meteorological Society*, **82**, 11, 2415-2434.

Beltrami, H. and Harris, R. N., 2001, "Foreword: Inference of climate change from geothermal data", *Global and Planetary Change*, **29**, 3, 149-152.

Beltrami, H., 2002, "Climate from borehole data: Energy fluxes and temperatures since 1500", *Geophysical Research Letters*, **29**, 23, 26-1.

Bhattacharya, A. and Mandal, M., 2015, "Evaluation of Noah land-surface models in predicting soil temperature and moisture at two tropical sites in India", *Meteorological Applications*, **22**, 3, 505-512.

Bosilovich, M. G. and Chern, J. D., 2006, "Simulation of water sources and precipitation recycling for the MacKenzie, Mississippi and Amazon River basins", *Journal of Hydrometeorology*, **7**, 3, 312-329.

Bosilovich, M. G. and Sun, W. Y., 1999, "Numerical simulation of the 1993 Midwestern flood: Land-atmosphere interactions", *Journal of Climate*, **12**, 5, 1490-1505.

Bosilovich, M. G., Robertson, F. R., Takacs, L., Molod, A. and Mocko, D., 2017, "Atmospheric water balance and variability in the MERRA-2 reanalysis", *Journal of Climate*, **30**, 4, 1177-1196.ications, *Journal of climate*, **24**, (14), 3624-3648.

Budyko, M. I., 1974, "Climate and life", Academic press.

Charney, J. G., 1975, "Dynamics of deserts and drought in the Sahel", *Quarterly Journal of the Royal Meteorological Society*, **101**, 428, 193-202.

Charney, J., Quirk, W. J., Chow, S. H. and Kornfield, J., 1977, "A comparative study of the effects of albedo changes on drought in semi-arid regions", *Journal of the atmospheric sciences*, **34**, 9, 1366-1385.

Chen, F. and Dudhia, J., 2001, "Coupling an advanced land surface–hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity", *Monthly weather review*, **129**, 4, 569-585.

Chen, F. and Zhang, Y., 2009, "On the coupling strength between the land surface and the atmosphere: From viewpoint of surface exchange coefficients", *Geophysical Research Letters*, **36,** 10, https://doi.org/10.1029/2009GL037980.

Chen, F., Manning, K. W., LeMone, M. A., Trier, S. B., Alfieri, J. G., Roberts, R., Tewari, M., Niyogi, D., Horst, T. W., Oncley, S. P., Basara, J. B. and Blanken, P. D., 2007, "Description and evaluation of the characteristics of the NCAR high-resolution land data assimilation system", *Journal of applied Meteorology and Climatology*, **46**, 6, 694-713.

Chen, F., Mitchell, K., Schaake, J., Xue, Y., Pan, H. L., Koren, V. Duan, Q. Y., Ek, M. and Betts, A., 1996, "Modeling of land surface evaporation by four schemes and comparison with FIFE observations", *Journal of Geophysical Research: Atmospheres*, **101**(D3), 7251-7268.

Cosgrove, B. A., Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Marshall, C., Sheffeild, J., Duan, Q. and Meng, J., 2003, "Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project", *Journal of Geophysical Research: Atmospheres*, **108**(D22).

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae. U., Balmaseda, M. A., Balsamo, G., Bauer, D. P., Bechtold, P. and Vitart, F., 2011, "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system", *Quarterly Journal of the royal meteorological society*, **137**, 656, 553-597.

Devanand, A., Ghosh, S., Paul, S., Karmakar, S. and Niyogi, D., 2018, "Multi-ensemble regional simulation of Indian monsoon during contrasting rainfall years: role of convective schemes and nested domain", *Climate Dynamics*, **50**, 11, 4127-4147.

Devanand, A., Huang, M., Ashfaq, M., Barik, B. and Ghosh, S., 2019, "Choice of irrigation water management practice affects indian summer monsoon rainfall and its extremes", *Geophysical Research Letters*, **46**, 15, 9126-9135.

Dirmeyer, P. A., Schlosser, C. A. and Brubaker, K. L., 2009, "Precipitation, recycling and land memory: An integrated analysis", *Journal of Hydrometeorology*, **10**, 1, 278-288.

Dudhia, J., 1989, "Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model", *Journal of Atmospheric Sciences*, **46**, 20, 3077-3107.

Dudhia, J., 1996, "A multi-layer soil temperature model for MM5", In Preprints, The Sixth PSU/NCAR mesoscale model users' workshop (22-24). Boulder, CO, USA: National Center for Atmospheric Research.

Ek, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grunmann, P., Koren, V. Gyano, G. and Tarpley, J. D., 2003, "Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model", *Journal of Geophysical Research: Atmospheres*, **108**(D22).

Georgescu, M., Weaver, C. P., Avissar, R., Walko, R. L. and Miguez-Macho, G., 2003, "Sensitivity of model-simulated summertime precipitation over the Mississippi River basin to the spatial distribution of initial soil moisture", *Journal of Geophysical Research: Atmospheres*, **108**(D22).

Hillel, D., 1980, "Applications of soil physics", Academic Press. New York. US.

Hong, S. Y., Lim, K. S. S., Lee, Y. H., Ha, J. C., Kim, H. W., Ham, S. J. and Dudhia, J., 2010, "Evaluation of the WRF double-moment 6-class microphysics scheme for precipitating convection", *Advances in Meteorology*, Jan 10.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P. and Stocker, E. F., 2007, "The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales", *Journal of hydrometeorology*, **8**, 1, 38-55.

Janić, Z. I., 2001, "Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model", Office note [National Centers for Environmental Prediction (U.S.)] ; p437

Kim, Y. and Wang, G., 2007, "Impact of vegetation feedback on the response of precipitation to antecedent soil moisture anomalies over North America", *Journal of Hydrometeorology*, **8**, 3, 534-550.

Klink, K. M., 1992, "Evaluating climate-vegetation interactions at climate model sub-grid scales", Ph. D Thesis, University of Delaware.

Koren, V., Schaake, J., Mitchell, K., Duan, Q. Y., Chen, F. and Baker, J., 1999, "A parameterization of snowpack and frozen ground intended for NCEP weather and climate models", *J. Geophys Res*., **104**(D16), 19569-19585

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P. and Yamada, T., 2004, "Regions of strong coupling between soil moisture and precipitation", *Science*, **305**, 5687, 1138-1140.

Lachenbruch, A. H. and Marshall, B. V., 1986, "Changing climate: geothermal evidence from permafrost in the Alaskan Arctic", *Science*, **234**, 4777, 689-696.

Liao, J., Tang, L., Shao, G., Su, X., Chen, D. and Xu, T., 2016a, "Incorporation of extended neighborhood mechanisms and its impact on urban land-use cellular automata simulations", *Environmental Modelling & Software*, **75**, 163-175.

Lim, H. S., Kim, H. C., Kim, O. S., Jung, H., Lee, J. and Hong, S. G., 2022, "Statistical understanding for snow cover effects on near-surface ground temperature at the margin of maritime Antarctica, King George Island", *Geoderma*, **410**, p. 115661.

Lim, Y. J., Byun, K. Y., Lee, T. Y., Kwon, H., Hong, J. and Kim, J., 2012, "A land data assimilation system using the MODIS-derived land data and its application to numerical weather prediction in East Asia", *Asia-Pacific Journal of Atmospheric Sciences*, **48**, 1, 83-95.

Liu, Y. Pan, Z., Zhuang, Q., Miralles, D.G., Teuling, A.J., Zhang, T., An, P., Dong, Z., Zhang, J., He, D. and Wang, L., 2015, "Agriculture intensifies soil moisture decline in Northern China", *Sci. Rep*., 5, 11261 doi:10.1038/srep11261 (2015).

Liu, Y., 2018, "Introduction to land use and rural sustainability in China", *Land use policy*, **74**, 1-4.

Mahrt, L. and Pan, H. L., 1984, "A two-layer model of soil hydrology", *Boundary-Layer Meteorology*, **29**, 1-20.

Maity, S., Nayak, S., Nayak, H. P. and Bhatla, R., 2022b, "Comprehensive assessment of RegCM4 towards interannual variability of Indian Summer Monsoon using multi-year simulations", *Theoretical and applied climatology*, **148**, 491-516.

Maurya, R. K. S., Mohanty, M.R., Sinha, P. and Mohanty, U. C., 2021, "Role of Soil moisture initialization in RegCM4.6 for the Indian summer monsoon simulation", *Pure and Applied Geophysics.* https://doi.org/10.1007/s00024-021-02853-5.

Mitchell, K. E., Lohmann, D., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A.Cosgrove, B. A., Sheffield, J., Duan, Q., Luo, L., Higgins, W., Pinker, R. T., Tarpley, D., Lettenmaier, D. P., Marshall, C. H., Entin, J. K., Pan, M., Shi, W., Koren, V., Meng, J., Ramsay, B. H. and Bailey, A. A., 2004, "The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system", *Journal of Geophysical Research: Atmospheres*, **109**(D7).

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J. and Clough, S. A., 1997, "Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave", *Journal of Geophysical Research: Atmospheres*, **102**(D14), 16663-16682.

Mohanty, M. R., Baraik, S. K., and Mohanty, U. C., 2023a, "Comprehensive Trend Analysis of Past Century Indian Summer Monsoon Rainfall and its Variability." *Global Journal of Human-Social Science*, *23*(B1), 25–38. https://doi.org/10.34257/GJHSSBVOL23IS1PG25

Mohanty, S., Swain, M., Nadimpalli, R., Osuri, K. K., Mohanty, U. C., Patel, P., & Niyogi, D. (2023b). Meteorological Conditions of Extreme Heavy Rains over Coastal City Mumbai, *Journal of Applied Meteorology and Climatology*, 62, 2, 191-208. doi: https://doi.org/10.1175/JAMC-D-21-0223.1

Mohanty, U. C., Sinha, P., Mohanty, M. R., Maurya, R. K. S. and Rao, M. N., 2019, "A review on the monthly and seasonal forecast of the Indian summer monsoon", *Mausam*, **70**, 3, 425-442.

Nayak, H. P. Nayak, S. Maity, S. Patra, N. Singh, K. S. and Dutta, S., 2022, "Sensitivity of Land Surface Processes and Its Variation during Contrasting Seasons over India", *Atmosphere*, **13**, 1382. https://doi.org/10.3390/atmos13091382.

Nayak, H. P., Osuri, K. K., Sinha, P., Nadimpalli, R., Mohanty, U. C., Chen, F. Rajeevan, M. and Niyogi, D., 2018, "High-resolution gridded soil moisture and soil temperature datasets for the Indian monsoon region", *Scientific data*, **5**,1, 1-17.

Nayak, H. P., Sinha, P., Satyanarayana, A. N. V., Bhattacharya, A. and Mohanty, U. C., 2019, "Performance evaluation of high-resolution land data assimilation system (HRLDAS) over Indian region", *Pure and Applied Geophysics*, **176**, 1, 389-407.

Oglesby, R. J. and Erickson, D. J., 1989, "Soil moisture and the persistence of North American drought", *Journal of Climate*, **2**, 11, 1362-1380.

Osuri, K. K., Nadimpalli, R., Ankur, K., Nayak, H. P., Mohanty, U. C., Das, A. K., & Niyogi, D., 2020, "Improved simulation of monsoon depressions and heavy rains from direct and indirect initialization of soil moisture over India." *Journal of Geophysical Research: Atmospheres*, *125*(14), e2020JD032400.

Osuri, K. K., Nadimpalli, R., Mohanty, U. C., Chen, F., Rajeevan, M. and Niyogi, D., 2017, "Improved prediction of severe thunderstorms over the Indian Monsoon region using high-resolution soil moisture and temperature initialization", *Scientific Reports*, **7**, 1, 1-12.

Paegle, J., Mo, K. C. and Nogués-Paegle, J., 1996, "Dependence of simulated precipitation on surface evaporation during the 1993 United States summer floods", *Monthly weather review*, **124**, 3, 345-361.5(4539), 1498-1501.

Pal, J. S. and Eltahir, E. A., 2001, "Pathways relating soil moisture conditions to future summer rainfall within a model of the land-atmosphere system", *Journal of Climate*, **14**, 6, 1227-1242.

Pielke Sr, R. A., 2001, "Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall", *Reviews of Geophysics*, **39**, 2, 151-177.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M. and Woollen, J., 2011, "MERRA: NASA's modern-era retrospective analysis for research and applications", *Journal of climate*, **24**, 14, 3624-3648.

Rind, D., 1982, "The influence of ground moisture conditions in North America on summer climate as modeled in the GISS GCM", *Monthly Weather Review*, **110**, 10, 1487-1494.

Robock, A., Vinnikov, K. Y., Srinivasan, G., Entin, J. K., Hollinger, S. E., Speranskaya, N. A. , Liu, S. and Namkhai, A., 2000, "The global soil moisture data bank", *Bulletin of the American Meteorological Society*, **81**, 6, 1281-1300.

Rodell, M., Houser, P. R., Jambor, U. E. A., Gottschalck, J., Mitchell, K., Meng, C. J.,Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D. and Toll, D., 2004, "The global land data assimilation system", *Bulletin of the American Meteorological society*, **85**, 3, 381-394.

Saha, S., Moorthi, S., Pan, H., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y., Chuang, H., Juang, H. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G. and Goldberg, M., 2010, "The NCEP climate forecast system reanalysis", *Bulletin of the American Meteorological Society*, **91**, 8, 1015-1058.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. and Teuling, A. J., 2010, "Investigating soil moisture-climate interactions in a changing climate: A review", *Earth-Science Reviews*, **99**, 3-4, 125-161.

Shukla, J. and Mintz, Y., 1982, "Influence of land-surface evapotranspiration on the earth's climate", *Science*, **215**(4539), 1498-1501.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D. and Stephens, S., 2002, "The drought monitor", *Bulletin of the American Meteorological Society*, **83**, 8, 1181-1190.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A., 2012,"An overview of CMIP5 and the experiment design", *Bulletin of the American meteorological Society*, **93**, 4, 485-498.

Vergopolan, N., Sheffield, J., Chaney, N. W., Pan, M., Beck, H. E., Ferguson, C. R. and Wood, E. F., 2022, "High-Resolution Soil Moisture Data Reveal Complex Multi-Scale Spatial Variability Across the United States", *Geophysical Research Letters*, **49**, 15, e2022GL098586.

Wei, J., Su, H. and Yang, Z. L., 2016, "Impact of moisture flux convergence and soil moisture on precipitation: A case study for the southern United States with implications for the globe", *Climate Dynamics*, **46**, 1, 467-481.

Yang, K., Zhu, L., Chen, Y., Zhao, L., Qin, J., Lu, H., Tang, W., Han, M., Ding, B. and Fang, N., 2016, "Land surface model calibration through microwave data assimilation for improving soil moisture simulations", *Journal of Hydrology*, **533**, 266-276.

Yoon, J. H. and Huang, W. R., 2012, "Indian monsoon depression: Climatology and variability", *Modern climatology*, **13**, 45-72.

Zhuo, L. and Han, D., 2016, "The relevance of soil moisture by remote sensing and hydrological modelling", *Procedia Engineering*, **154**, 1368-1375.