EVALUATING LAND USE & LAND COVER CHANGE IMPACTS ON RAINFALL FORECAST OVER THE NORTH-EASTERN REGION OF INDIA USING THE WEATHER RESEARCH AND FORECASTING MODEL

Major Project Dissertation

Submitted By:

AKRITI YADAV

For the partial fulfilment of the

Degree of Master of Science in

GEOINFORMATICS

Submitted to

Department of Energy and Environment

TERI School of Advanced Studies

May 2020

DECLARATION

This to certify that the work that forms the basis of this project "EVALUATING LAND USE & LAND COVER CHANGE IMPACTS ON RAINFALL FORECAST OVER THE NORTH-EASTERN REGION OF INDIA USING THE WEATHER RESEARCH AND FORECASTING MODEL" is an original work carried out by me and has not been submitted anywhere else for the award of any degree.

I certify that all sources of information and data are fully acknowledge in the project Dissertation.

AKRITI YADAV

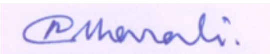
Dated: 27-05-2020

CERTIFICATE

This is to certify that Akriti Yadav has carried out her requirement project in partial fulfilment of the requirement for the Degree of Master of Science in Geoinformatics on the topic "Evaluating Land use & Land cover change impacts on Rainfall over the North-Eastern Region of India using the Weather Research and Forecasting Model" during January 2020 to May 2020. The project was carried out at North Eastern Space Applications Centre (NESAC), Government of India, Department of Space, Umiam Shillong, Meghalaya.

The Dissertation embodies the original work of the candidate to the best of our knowledge.

Dated: 27-05-2020



Rekha Bharali Gogoi
(External Supervisor)
Scientist 'SE'
North Eastern Space Application Centre
Govt. of India, Dept. of Space
Umiam, Meghalaya-03

Dr Vinay Shankar Prasad Sinha
(Internal Supervisor)
Associate Professor
Department of Natural Science
TERI School of Advanced Studies
Vasant Kunj, New Delhi-70

Dr Sudipta Chatterjee
Associate Professor and Head
Department of Natural Science
TERI School of Advanced Studies

ACKNOWLEDGEENT

I take this opportunity to express my sincere gratitude and profound appreciation to my supervisor Rekha Bharali Gogoi, Scientist 'SE', Space and Atmospheric Department, North Eastern Space Application Centre, for giving me an opportunity to work under her supervision. She has been very helpful and supportive throughout the whole work. Her technical expertise and availability round the clock to respond to my numerous queries motivated and kept me on the right track during the project. It was really a nice experience to work at NESAC.

I would really like to thank my internal guide Dr Vinay Shankar Prasad Sinha, Associate Professor, Department of Natural Science, Teri School of Advanced Studies, for his guidance and timely advice during dissertation work.

I am thankful to Dr Nithiyanandam Y., Major Project Coordinator, Department of Natural Science, TERI School of Advanced Studies, for his kind support during dissertation work. I would also like to express my deep regards to all the professors of Department of Geoinformatics for their guidance and valuable support throughout this project.

I owe my wholehearted thanks and appreciation to my family and classmates for their valuable support. I hope that, I can build upon the experience and knowledge gained during this time period and make a valuable contribution to future studies.

Akriti Yadav

1800020MSG

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

NWP	Numerical Weather Prediction
WRF	Weather Research and Forecasting
NER	North-Eastern Region
LULC	Land Use Land Cover
GIS	Geographical Information System
AWiFS	Advanced Wide Field Sensor
SWM	South West Monsoon
NCEP	National Centre for Environmental Prediction
GFS	Global Forecast System
UTC	Universal Time Coordinated
USGS	United States Geological Survey
IMD	Indian Meteorological Department
MODIS	Moderate Resolution Imaging Spectroradiometer
IGBP	International Geosphere Biosphere Programme
RMSE	Root Mean Square Error

LIST OF FIGURES

LIST OF TABLES

Annexure

ABSTRACT

Modeling extreme precipitation events is a continuing challenge in many domains, as these events rely on multi-scale interactions, as well as on configuration of model like initialization schemes, spacing of grid and physical parameterizations. Heavy precipitation events in every part of the world are responsible for massive floods. In recent years, Numerical Weather Prediction models including Weather Research and Forecasting model (WRF), forecasts and simulations of weather conditions for the future have become an essential part of the research, in the domain of both hydrology and atmospheric sciences in the recent years. In case of forecasting, the performance of modeled forecast has therefore became a matter of utmost importance. In addition, variations in land use land cover (LULC) have been shown to have significant effects on climate across various pathways that modulate rainfall and land surface temperature. With this context, the WRF model is being incorporated in the present study to evaluate the impact of land use and land cover changes on rainfall forecast. The model was implemented with 3 types of different land use data sets viz. MODIS data, USGS and AWiFS (ISRO) land use data. The research was carried out for India's North Eastern Region (NER). In the present study, the efficiency of WRF model is assessed by comparing the model simulated rainfall with the observational gridded rainfall data (0.25 0.25) from IMD. In addition, BIAS and RMSE are determined for each experiment. Results reveals that the impact of land use and land cover changes on rainfall forecast and other associated meteorological parameters such as surface wind, humidity, dewpoint and surface temperature. It is found that the high-resolution and updated AWiFS ISRO land use data improves the model forecast to a significant extent in comparison to USGS and MODIS which highlights the importance of land use land cover effect in atmospheric process with the need for an updated LULC for meteorological modeling.

Keywords: Numerical Weather Prediction, Weather Research & Forecast (WRF), LULC, USGS, MODIS, Bias, RMSE.

CHAPTER 1: INTRODUCTION

1.1Background:

The Indian summer monsoon is a major phenomenon that plays a vital role in both the global water cycle and the global climate system (Trenberth, et al., 2000). Variations in rainfall pattern have the most adverse effects on mankind of all meteorological factors. Most specifically, the main concern is about the extreme rainfall changes. Since, extreme rainfall conditions frequently lead to disasters such as flash flooding, which in effect causes extensive damage to the environment as well as natural habitats (Roy, et al., 2018). Every year, North-Eastern region (NER) of India suffers from devastating flood resulting in to huge loss of revenue and life. Thus, accurate calculation and prediction of the summer monsoon precipitation is essential for all applications.

Numerical Weather Prediction is among the most advanced weather forecasting techniques. It uses the present weather knowledge to predict future weather condition using atmospheric and ocean mathematical models. This technique requires very high computation facilities like supercomputers. In addition to that, the forecast skills are limited to only six days even with usage of supercomputers. Atmospheric and ocean simulations use algebraic equations, which cannot be exactly determined, and over time, the error increases. In addition, heat exchange, solar radiation parameterizations, moisture which include precipitation & clouds, water, terrain, vegetation, and soil properties impact are used in the model. In several studies, global models are being used to explain the wide scale circulation movements and pattern as well as to statistically evaluate the rainfall, but they seem unable to reflect the local to regional characteristics. of monsoon weather, due to their coarser resolution. Regional models may thus clearly simulate the interaction between the wide-scale regional topography and weather system, allowing accurate climate simulations. (Gadgil & Sajani, 1998; Srinivas, et al., 2012; Ratna, et al., 2011) . Additionally, regional climatic models has a strong convection system and representation, thereby reducing one of the main sources of errors and uncertainty that occurred mostly in the global models and become a popular alternative for the study of annual monsoon’s rainfall. The ‘ *Advanced Research Version(ARW) of the weather research and forecast model’* (hereinafter also known as the WRF model) is a common atmospheric and regional community model particularly used in both analysing and predicting a large number of high-impact meteorological events, such as tropical cyclones, pattern of rainfall and thunderstorms (Skamarock, et al., 2005; Madala, et al., 2014; Osuri, et al., 2017) . However, severe rainfall incidence on shorter timeframes in rugged terrains is especially difficult to forecast and remains a concern for scientific and communities (Das, et al., 2008).

Although, efficiency of a numerical model is depending strongly on the model boundary and initial conditions but the geographical static data also plays a significant role. One such important parameter is land use and land cover data. Land use and land cover (LULC) not only have impacts on human activities but also on climate. Land use type is an important parameter of the land surface that demonstrates the exchange of heat & momentum amongst the land surface and air. The earlier shows that, the land use and land cover data may influence meteorological simulations significantly. Consequently, changes in LULC were well-thought-out as one of the main factors influencing the climate at regional level and the reason for climate change. Lands surface plays a critical role particularly in driving the formation of boundary layers and, eventually, precipitation patterns. Improper depictions of the present land state, especially spatially specific fields such as land-cover, biophysical and topographical parameters subsidize the uncertainty in the weather simulations of the model that range from local to regional scales. Accurate evidence on land cover is of critical significance in atmospheric model studies. Existing land use land cover data used in climatic models at regional level, for instance USGS and MODIS, are not always up-to-date. USGS LULC data is obtained from 1km AVHRR data available from 1992 (April) to 1993 (March) and MODIS IGBP land use data based on the MODIS satellite data is a 20 category land use data which was collected during the years 2001-2005. In India, ISRO has made an effort to obtain LULC data sets from Indian satellite IRS P6 AWiFS derived in WRF model format suitable for Numerical Weather Prediction and different climatic model practices. All Indian region of USGS data is substituted with AWiFS the derived data and the final product is a global USGS LULC data with the Indian region substituted by AWiFS based LULC having the basic resolution at 56m that is more updated and precise at a annual basis for the period of 2004-2005 to 2012-2013 (Technical Report, NRSC, ISRO, 2014).

In the last few decades, the North-Eastern region of India has also seen massive urban development. Many green areas and agricultural land have been altered into built-up and commercial areas. The 24-class default USGS land use data being very old, is used in the WRF model for mapping land use to simulate the domain and is also ineffective in terms of the actual illustration of land use. Significantly, there is a considerable discrepancy: between the land use data which contributes to performance of the model An up to date land use data, therefore, come up with a better extent for model performance enhancement in terms of rainfall forecast over NER.

1.2 Study Area:

A land of beautiful landscape, mostly hilly abounded by rich forest and natural resources, Northeast India is amazing place for everyone. The India's Northeast region covers an area of 255,036 sq. km. representing about 7% of the country.

The north-eastern area is distinguished by three geographical characteristics, namely the Brahmaputra plains, Eastern Himalayas and the Barak Valley. But after independence, the country was so partitioned that the eastern part of the then Bengal consisted of Bangladesh, almost separating the north-eastern part of India from the rest part of the country, except for a small corridor about 40km wide along Nepal and Bhutan Himalayan foothills. Whereas this corridor was built between 3 countries. Bangladesh, Nepal, Bhutan and much of north-eastern India are surrounded by 4 foreign countries: Bangladesh, Myanmar, Bhutan and China in particular.

1.2.1 Physiography:

The North-Eastern Region of India can be physio-graphically classified into the *'Eastern Himalayan, the Patkai, Barak valley, and the Brahmaputra plains.* North-eastern part of India has predominantly a sub-tropical climate with hot and humid summers, mild winters and acute monsoon.

1.2.2 Location:

Northeast India is located between "24°N - 28°18′N lat, and 89°46′E - 97°4′E lon". It includes 8 states of India viz: Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura and Sikkim . The total geographical area of the region is up to 255,036 sq.km, representing only about 7 percent of the country.

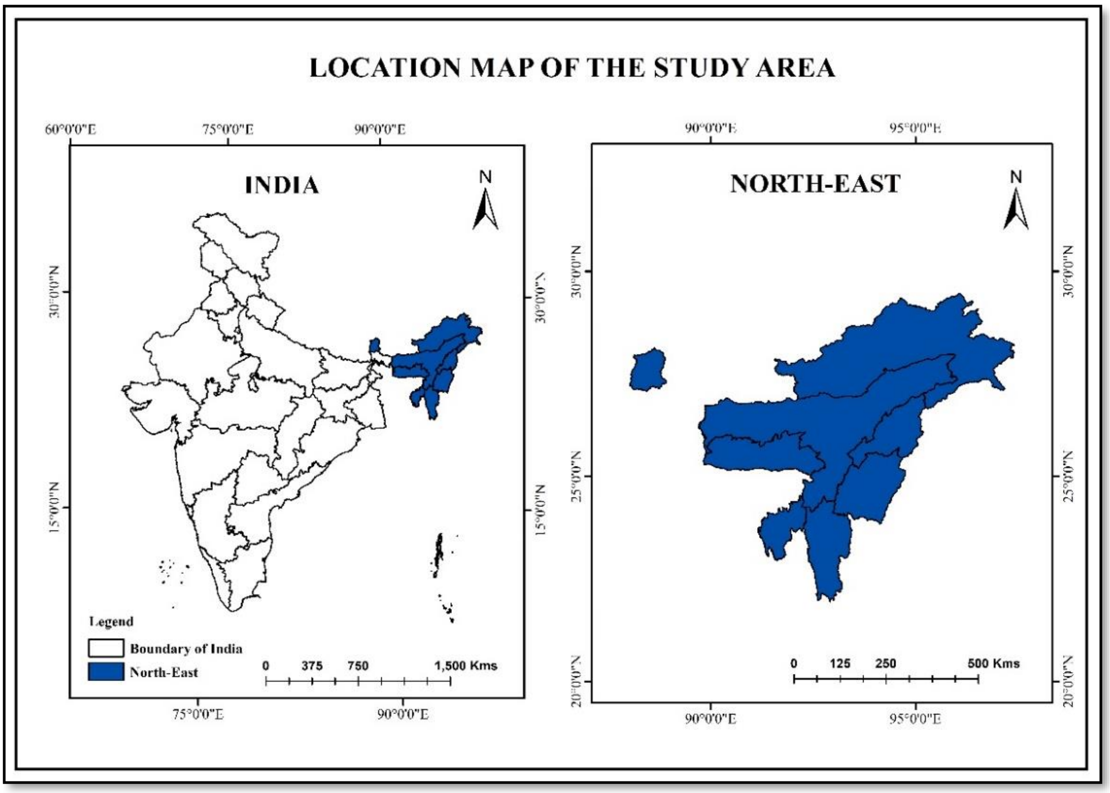


Figure 1: Location Map of the North East India

1.2.3 Climate:

The Northeast Region(NER) of India has a sub-tropical climate which are affected by its relief and is influenced by the northeast and the southwest monsoons (Dikshit & Dikshit, 2014). The climate is greatly influenced by the Himalayas to the north, the Mizoram, Manipur and Meghalaya plateaus in the south and the Nagaland hills to the east. When the monsoon winds originates from the Bay of Bengal and then later it move towards the northeast, the mountains present there force the moist winds to move upwards, which cause them to cool by the adiabatic process and it finally condenses to form clouds, causing heavy rainfall on these slopes (Dikshit & Dikshit, 2014) . The daily temperature in the plains of Barak Valley and Brahmaputra, also including the western part of Mizo Hills and Tripura which are generally around 15°C in January, whereas the temperature in other parts of the region is between 10℃-15℃ .

1.2.3.1 Rainfall:

Northeast India is known as the country's rainiest area, as many places that receive an average annual rainfall of 2,000 mm and above create ecosystem and flood problems. The rainy season occurs during the monsoon season primarily in the summer. Mawsynram and Cherrapunji in the Meghalaya plateau are the world's rainiest areas with an annual rainfall of about 11,418.7 mm. The southwest monsoon is responsible for bringing to this area 90 per cent of the annual rainfall. April to late October are the months in which practically the rainfall occurs and in June and July the amount of rainfall is highest as a result of Northeast India's rainiest months . The southern parts of the region are the receives monsoon first (End of May or June) while northern mountain as well as Brahmaputra valley receives later.

1.2.4 Soil:

Soil is among the most important factor in the natural resources, and is the top layer of the surface of the earth. It consists of a mixture of organic matter, liquids, fine powdered rocks, various minerals and many other species. The soil type is determined by the proportion of the key ingredients. But also affects a number of factors for instance weather, topography, anthropogenic activities for e.g., fishing, gardening, grazing etc also influence soil formation (DSR, 2017). The soil of Northeast India is generally distributed on the basis of altitudes as: a) mountain soil over higher altitudes, and b) laterite soil over medium altitude, while c) the lower altitude has red soil.

1.2.5 Land use:

Land use and land cover includes the natural landscape or forest for building environment such as settlements and semi-natural habitats such as pastures, managed woods and arable fields. They are instantly linked to human activity on their surroundings. Land use land cover in North-East signifies a distinct pattern as it relates to the rest of the country. Approximately 35 percent of the region's territory is plain except Assam where plain is about 84.4 percent of its geographic area (GA). Near to 15.7% of the GA area is under cultivation; forest cover (open and dense) in the region ranges from 40.2% (Assam) to 72.99% (Arunachal Pradesh).

In Northeast India, shifting agriculture invaded 2.88 percent (0.754 Mha), while Grasslands occupied 6.06 percent, wastelands occupied 6.22 percent and approximately 4.53 percent is occupied by water bodies.

1.3 Rationale of the Study:

Reliable estimations of extreme rainfall events are needed for predicting floods accurately. There are several studies that have investigated and demonstrated the positive effects of evaluating changes in land use and land cover on the rainfall forecast (both conventional and satellite based) using the Weather Research and

Forecasting model for the weather systems all over India. However, most of the studies focused on predicting rainfall, tropical cyclones and thunderstorms using WRF Model. No studies exist in the literature that have quantified and documented use of, land use land cover change impacts for the simulation of severe weather systems like extreme rainfall events using Numerical Weather Prediction models over North-Eastern Regions of India.

1.4 Aims and Objectives:

Aim: The key aim of the research project was to evaluate the impacts of change in the land use land cover on rainfall prediction using the WRF model i.e. Weather Research and Forecasting model over the North-Eastern region of India.

Objectives: The objectives are as follows:

1) To simulate monsoon rainfall over north-eastern region of India using WRF model for 3 different land use land cover (LULC) categories.
2) To analyse the LULC data for significant changes.
3) To study the impact of land use land cover changes on WRF rainfall forecast.

CHAPTER 2 - LITERATURE REVIEW

This chapter, emphasize the various studies and several fundamental principles relevant to numerical weather forecasting, forecasting model (WRF) and weather research and the use of land and changes in land cover.

2.1 About Numerical Weather Prediction (NWP):

The Numerical Weather Prediction models are dynamic and the costliest than any other computing tools in this world. This concept comprises an interpretation module, that converts irregular distribution of weather measurements into a derived data structure utilized for the NWP concept. Second, the numerical portion includes hydrodynamic equations which are iterated at each time stage. The vertical and horizontal resolution of the realm must be carefully characterized. Technology supports a boundary requirement to operate inside a specific region that is a subdivision of a global network run. Models operating on NWP should be in three dimensional. A fairly complex parameterization of physical processes (Meyer, 1993) is included by the physical component of the defined model.

2.2 Validation of Forecast from the NWP models:

Numerical Weather Prediction have increased success with better skill scores over the last few years as a consequence of the development of enhanced model parameterization systems, higher computational efficiency, and data assimilation techniques (Mitra, et al., 2013). Nevertheless, the development in skills for tropical monsoon prediction has not yet been fully understood (Prakash, et al., 2014) . Given if there is certain distortion in this region in the event of rainy season forecasts, there is still no accurate prediction of the climate change outlook for Indian summer monsoon precipitation (Turner & Annamalai, 2012). Advancement of the experiment depends on the software precipitation evaluation that serves as a main input for this reason. In addition, validating the accuracy of the model against the calculated data is critical for few determinations. (Ebert, et al., 2007; Collins, et al., 2013).

In NWP, all the real-time climate and weather condition are used as an input for operating atmospheric simulations for forecasting the weather progression. Further, the atmosphere is conceive as a complex fluid in NWP models and thus, it also reflects the behaviour of the atmosphere through determining mechanical and thermodynamic equations (Yu, et al., 2016).

The variability of meteorological evidence is also generally the key source of instability in the flood prediction in the performance assessment of flood prediction for previous flood events (Rossa, et al., 2010). Outputs from Meteorological Prediction Tool, that is 'Weather Research and Forecast (WRF)' are used as the key input over the duration of the forecast time. It is therefore important to check the uncertainty of the data modeled by the WRF.

2.3 Weather Research and Forecasting Model (WRF):

The WRF is an updated version 5 (MM5) of the PSU / NCAR mesoscale model with various advantages such as the high-resolution: time patterns and yearly obtained numerical mean. WRF manages to captures precipitation better than TRAMPER and MM5 (Gsella, et al., 2014).

Simulations carried out throughout the Eastern part of India using the WRF-NMM model indicate strong thunderstorm forecast. With good accuracy the model records rainfall intensity rates (Litta, et al., 2012). Effectiveness of WRF-ARW variant tested for severe precipitation incidents in Ahmedabad (Gujarat), India suggests that the KF and GD programs underestimate the frequency of precipitation (Deb, et al., 2008). Ravindranath, et al., (2010) adds the – AWiFS data from the IRS P6 satellite of the WRF model for land use cover classification. The data used was for the year 2007-2008 over the Indian region. The study shows that there are significant effects over the Jammu & Kashmir region and there is almost no improvement in all other regions compared to land use land cover by USGS.

2.4 Previous work using WRF Model:

Hereafter , the WRF model also referred as advanced research version of the Weather Research and Forecasting model, is a common regional community model commonly used both for analysing and predicting a range of several high-impact meteorological events for instance tropical cyclones. (Raju, et al., 2011; Routray, et al., 2016), rainfall (Vaidhya & Kulkarni, 2007; Deb, et al., 2008; Chang, et al., 2009; Mohanty, et al., 2012), and thunderstorms (Madala, et al., 2014; Osuri, et al., 2017a).

Within the literature many works are mentioned that have contemplate the WRF model over and around the Himalayan domain. Kumar, et al., (2012) has used the same model for the simulation of 2010 cloud burst over the north-western belt of the Himalayas, in the Leh region, although Thayyen, et al., (2013) and Kumar, et al., (2014) utilized the WRF model to gain insight into the atmospheric processes dating back to the year 2010 Leh incident.

Correspondingly, Chevuturi, et al., (2015) has used the WRF model to replicate the September 2012 extreme precipitation occurrence in the central Himalayas. Medina, et al., (2010) also used the WRF model to clarify the conditions to show how the topography and and surface factors in the western and eastern part of Himalayas affect the extreme convection. The WRF model is also being used in many studies , especially in the 2013 ,Uttarakhand region heavy rainfall event, inclusive of those by Kotal, et al., (2014), (Vellore, et al., 2016) and Hazra, et al., (2017). To acknowledge the physical processes, prime to the incidence, Shekhar, et al., (2015), (Dimri and Chevuturi , 2016), moreover Dimri, et al., (2016) accomplish extensively synoptic survey of the June 2013 s heavy precipitation event utilizing the WRF model. Rajesh, et al., (2016) propose the function of conditions of land surface in the simulation of the heavy rainfall incidence.

As a result, it can be derived from pre-existing literature that the regional climatic model is performing acceptably well throughout the world. However, the determination of the optimal group of physical parameterization schemes (together with the segregation of correct reference grid and resolution models) to immensely heavy precipitation occurrences and the interpretation of the impact of static spatial data on rainfall evaluation across the Indian monsoon region is even now a vital area of research.

2.5 Land use and Land Cover Changes:

An important parameter, land use land cover (LULC) is affecting human life and the environment. It normalizes the momentum and the heat exchange between soil and air that defines the computation of near-surface meteorological magnitudes in numerical models (Jim & Sistach, 2004).

LULC transition matrix is used by Li , et al., (2018) in their paper to discuss shifts a decade before millennium (BM) and a decade after the millennium (AM) to research the effects of use of land and ground cover adjustments in meteorology in a systemic manner. In January and July, the Weather Research and Forecasting (WRF) model was accustomed to simulate precipitation, speed of wind and air temperature using the 1990, 2000 and 2010 LULC data. They conclude the study by suggesting that, a full discourse on the effect of LULC shifts on the climate will help potential creation of substantially more biologically friendly and efficient planning of land.

In various experiments, the WRF model was used to check the consequence of LULC dynamics on microclimates (Hong, et al., 2009; Mahmood, et al., 2011; Wang, et al., 2015). Zhang, et al., (2010) used the WRF model for the inspection of microclimate change in China and they found that cropland conversion to urban areas increased precipitation and temperature both, nonetheless decreased humidity of surface, with a considerable effect in summer in compared to winter.

Grossman-Clarke, et al., (2010) investigated that the effect of urbanization on near-surface air temperatures was explored by combining WRF model with Noah Urban Canopy and draw the inference that the largest rise in temperature transpire as irrigated agricultural land was reinstate by developing areas. Under the threat of rapid growth of population, built-up areas and agricultural lands are generally growing at the cost of wetlands as drained wetlands can easily be turned into urban areas or croplands (Scoones, 1991). There is an urgent need to determine the degree to which the microclimate could be amended due to the shrinking of various Land use categories.

2.6 Heavy Rainfall Events in North-East:

On 1st June 2018 Monsoon advanced into parts of Mizoram and Manipur and remaining parts of: Nagaland, Tripura, Manipur and Mizoram and some parts of Assam and Arunachal Pradesh. Between 9th and 12th June 2018, the South-West Monsoon (SWM) advanced steadily into most parts of West Bengal, Odisha, and Chhattisgarh. The maximum rainfall in this area is received in July month. Resultantly, 2018 July month was selected for the experiment.

CHAPTER 3: MATERIALS AND METHODS

This chapter illustrates the meteorological data and land use and land cover data used for the study. This segment further fine points the methodological steps to carry out this study.

3.1 Data Used in the Study:

The data used in this research are meteorological data such as Global Forecast System and IMD Rainfall Data and Land use and Land Cover data provided by different agencies.

3.1.1 Meteorological Data:

Meteorological data used in this study are obtained from 'National Centre for Environmental Prediction (NCEP) Global Forecast System (GFS)' data and to validate the result IMD Gridded Rainfall data have been used.

3.1.1.1 Global Forecast System (GFS) Data:

Abiding data records are needed from ground-based stations to supply the atmospheric conditions properly at the synoptic-scale, or grid-points evenly distributed right through the area of concern. At such a wide network generally the ground-based data is not accessible. In consequence, National Centre for Environmental Prediction (NCEP) Global Forecast System (GFS) data that provides '*sea level pressure, sea surface temperature, humidity, soil temperature, air temperature, vertical wind velocity, skin temperature, soil moisture, wind direction*' etc. and vertical moisture at 0.25° grids viable at every 00 UTC was used in this research to; impart the prime and boundary conditions.

3.1.1.2 IMD Rainfall Gridded Data:

For comparing the model simulated rainfall output, IMD gridded rainfall data have been used. This data product is a daily framed rainfall data (0.25^o x 0.25^o).

3.1.2 Land Use Data:

The model was implemented with three distinct types of land use data viz. a) USGS, b) MODIS and c) ISRO Land use data.

3.1.2.1USGS Land Use Data:

The 24-category U.S. Geological Survey (USGS) Global Land Cover Characterisation (GLCC) LULC dataset was derived from 1-km AVHRR data spanning April 1992 through March 1993.There are 24 distinct categories of land use in this particular dataset, that is default USGS land use dataset under the WRF model.

3.1.2.2 MODIS Land Use Data:

MODIS based land use recorded data is derived by monitoring a yearly input of Terra and Aqua data comprising 20 land cover classes determined by the International Geosphere Biosphere Programme (IGBP) . The data record that comes with WRF (up to v3.5) is contingent on the year 2001. Lately, with the release of updated WRF version 3.6, MODIS land use data record is also accessible at resolution of 15 secs (~ 500 m).

3.1.2.3 ISRO Land Use Data:

Land Use / Cover Map for the whole country at scale of 1:50,000 is prepared once in 5 years using three season data. Similarly, after 2004-05, 14 cycles of Land Use / Cover Mapping have done at a scale of 1:250,000. Bhuvan Geoportal provides an online process with the actual digital map for further exploration. The LULC product used in this research is a worldwide USGS LULC data with the Indian region substituted by the basic 56m resolution AWiFS based LULC prepared by ISRO and adopted for mesoscale models, for the year 2012-2013.

Table 1: Data Used and its Specifications

Sl No.	Data Used	Specifications	Time Period
1..	USGS Land use data	24 default categories of different land use data. Data set derived from AVHRR. Having 1-km resolution.	April 1992 – March 1993
2.	MODIS– based land use data	20 land cover classes demarcated by IGBP. MODIS land use dataset have resolution of 15 sec and 30 sec (~ 500 m)	2001
3.	ISRO Land use Data	Land use land cover map for the entire country obtained from 56 m resolution AWiFS.	2012-2013
4.	Global Forecast System (GFS)	Forecast time steps at a 1-hourly interval.	July 2018
5.	IMD Rainfall Gridded Data	Spatial Resolution (0.25X0. 25 degree) Long Period (1901-2018)	July 2018
6.	Era Interim Data	Spatial resolution ~14 km (0.125° grids) with 60 vertical levels.	July 2018

3.1.3 Climate Reanalysis Datasets

ERA-Interim project is one of the main global products of climatic re-analysis from (1979) onwards, continuously being restructured in real time. The framework consists of 4D (4D-Var) analysis, with a 12-hour analysis period. The available data sets have a spatial resolution of 80 km (0.75-degree grids) on 60 vertical surface rates up to 0.1 hPa. However, the data can be downloaded at higher resolution as well. Era-Interim reanalysis data consist of surface meteorological parameters such as wind at 10-meter height (u10, v10), dewpoint temperature at 2-meter height (d2m), temperature at 2-meter height (t2m) are downloaded at 0.125-degree resolution for this study.

3.2 Methodology:

This part describes about the configuration of domain, model setup, physical parameterization, LULC data uses and experimental Design This segment further describes evaluation methods used to validate the results.

3.2.1 Domain Configuration:

In this study, the WRF model was configured for two domains. Domain 1 and Domain 2 have a spatial resolution of 27 Km and 9 Km respectively (Figure 2).

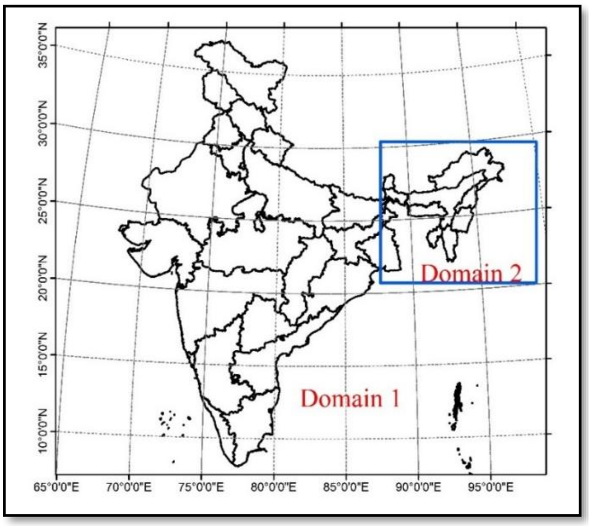


Figure 2: Domain Configuration

Domain 1 covers the major part of India and with number of grids-180*180. Domain 2 has a 185*185 grid increment covering most area of India's North-eastern Region (Table 2). The National Centre for Environmental Predictions (NCEP) Global Forecast System (0.5° x 0.5°) resolution corresponding to 00:00 UTC of every day for the month of July 2018 has provided the prime and boundary conditions for the meteorological fields.

Table 2: Domain Specification

Central Lat Lon	21°N 88°E
Number of grids	Domain 1(180 × 180), Domain 2 (185 × 185)
Horizontal Resolution	Domain 1 (27km), Domain 2 (9km)
Vertical levels	36
Time step	120 sec
Projection	Mercator

3.2.2 Model Setup:

In the present research work, the updated WRF model version 3.8 is used for forecasting rainfall and other rainfall forcing atmospheric parameters. The Weather Research and Forecasting (WRF) model is an atmospheric simulation and Numerical Weather Prediction (NWP) system. The Advanced Research WRF (ARW) is applicable for use in a wide range of applications beyond scales ranging from a few meters to thousands of kilometres, like real-time Numerical Weather Prediction, regional climate research, hurricane research etc. (Skamarock, et al., 2008).

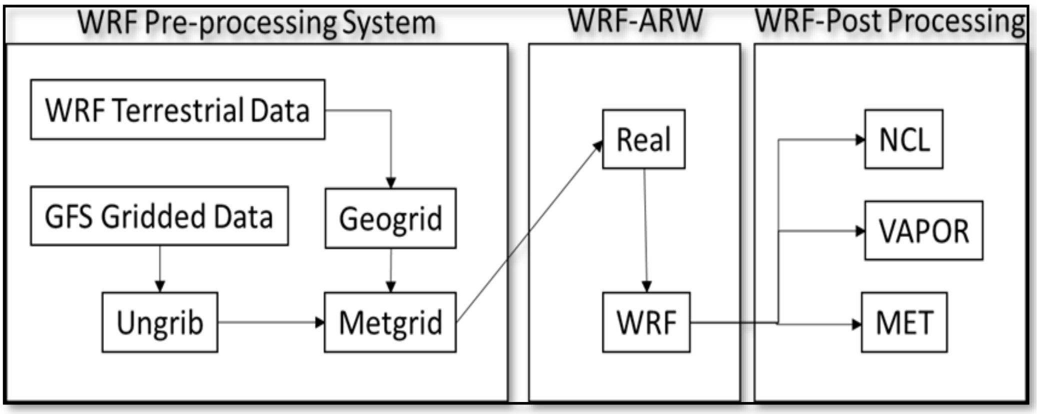


Figure 3: Flow chart of the WRF Model

The WPS is an array of programs that takes terrestrial and meteorological data (typically in GriB format) and remodels them for input to the ARW pre-processor program for real data cases (Real). The above figure displays the flow of data in and out of the WPS system. The processes which include in the WPS program are as follows:

- **Geogrid:** Physical grid definition (including the location on the globe, nest locations, projection type, number of grid points, and grid distances).
- **Ungrib:** Interpolation of static fields to the prescribed domain.
- **Metgrid:** Reformatting of GriB data into an internal binary format. Interpolation of meteorological data.

WRF_REAL: Two ARW core scripts of WRF model are processed to dynamically downscale the GFS data into the model domain at specified times which are as follows:

1. *real.exe real data initialization module* interpolates meteorological data obtained from WPS to vertical model levels and generates initial and boundary data, required as input to the wrf.exe model. After that, two files have been created: "*wrfbdy_d01 & wrfbdy_d02, to implement boundary conditions, and wrfinput_d01 & wrfinput_d02*", to provide initial conditions for each domain respectively.
2. *Integration of wrf.exe code* Numerically approximate the solutions to the model equations to produce a forecast.

3.2.2.1 Physical parameterizations:

The WRF model has a wide range of physical parameterisations available. In addition, the selection of the parameterisation scheme directly influenced the WRF model's simulation performance. Jin, et al., (2010) compared the effects on temperature and precipitation simulations of four land surface parameterization schemes and noted that the Noah land parameterization was more reliable for winter weather. In addition, Jianjun, et al., (2014) used Noah's land surface model to simulate conditions in China and achieve accurate outcomes. The physical parameterizations we used are shown in Table 3.2 based on preceding studies.

Table 3: Physics and Dynamic options of WRF Model

Options	Scheme
Microphysics	Thompson Graupel Scheme
Cumulus Option	New Grell Scheme
Long Wave Radiation	RRTM Scheme
Short Wave Radiation	Dudhia Scheme
Surface Layer Option	Monin Obukhov
Land Surface Option	NOAH LSM
PBL	MYJ Scheme
Time Integration Scheme	Third-order Runge-Kutta
Horizontal Grid	Arakawa C grid

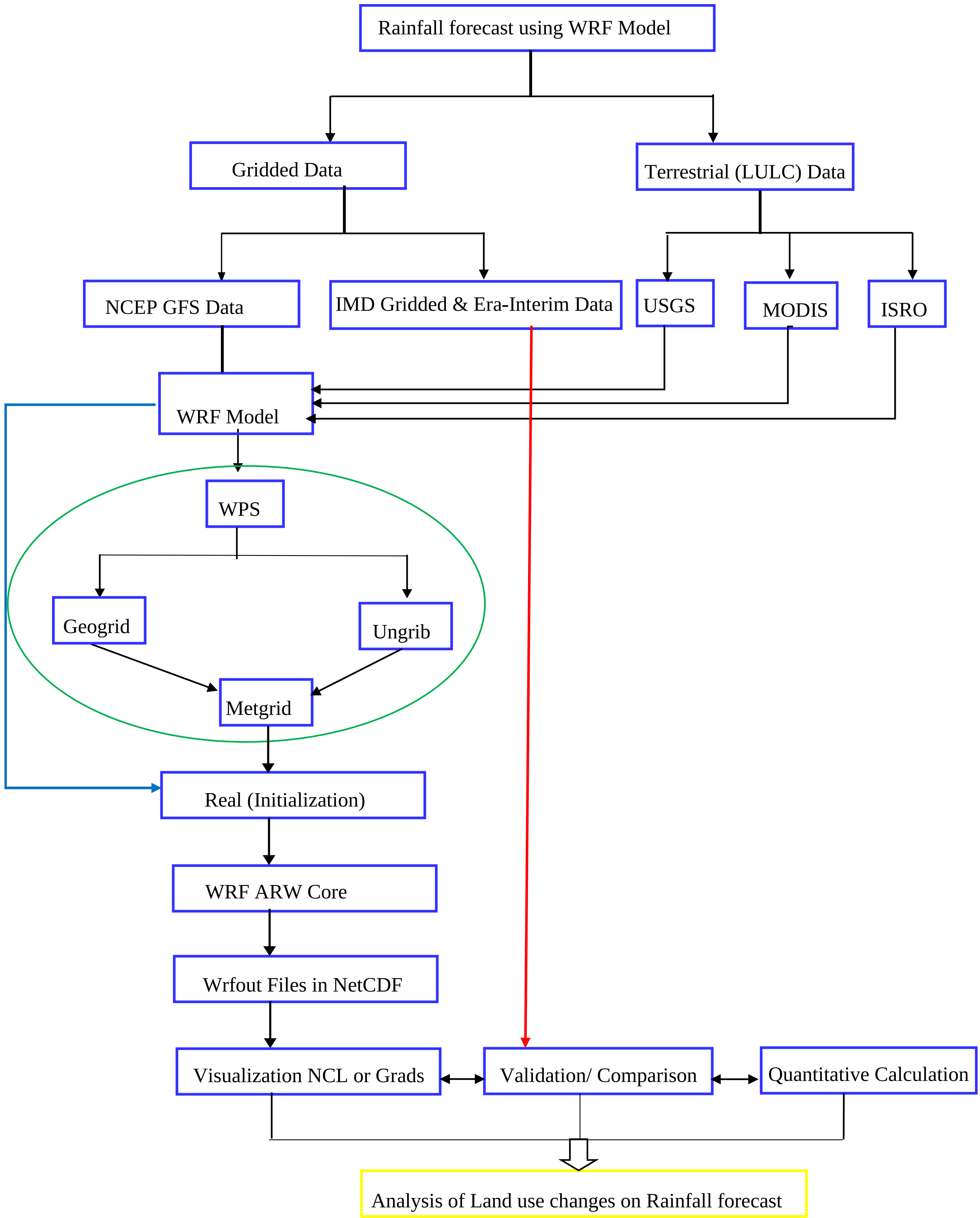


Figure 4: Flowchart of Methodology

3.2.3 Land use Land-cover (LULC) data uses:

Land use and land cover is one of the significant soil surface parameters that affect the surface skin temperature strongly. In the present study, the impact of land use land cover changes on rainfall simulation was studied. The MODIS and USGS LULC are standard sets of LULC data which comes with WRF-ARW package. The IRS P6-AWiFS Land Use/Land Cover is a product of ISRO, that has an extension of the default USGS land use land cover data, having very fine resolution than USGS. The AWiFS LULC data for the WRF model can be downloaded from http://bhuvan.nrsc.gov.in/data/download/index.php. The modified LULC map of North east region was prepared for the three cases by reclassifying the classes. MODIS IGBP's 20-class LULC data has been reclassified into 24 USGS classes.

The only variable factor in this study was the change in LULC, and the remaining parameters were held the same manner to explicitly discover the effect of LULC changes on rainfall forecast in North-East Region (NER).

3.2.4 Experimental Design:

For the month of July, simulations were performed with three separate LULCs, i.e. USGS, MODIS and ISRO, using meteorological data from GFS (0.5 °). The three experiments are named as USGS, MODIS and ISRO. Monsoon rains are received in the month of July-September by the Indian continent, and the heaviest rain month is recorded in July. As July is the month that receives the highest rainfall, therefore this time period selected is acknowledged to be the peak monsoon season in the region. The initial analyses for all the experiments are generated 24 hours prior to the first analysis to spin-up the model. All total 180 simulations are conducted for the three experiments from 1st July 2018 to 31st July 2018 for both the domains. An overall workflow is shown in Figure 4.

3.2.5 Evaluation Method:

This study undertakes a comprehensive evaluation of the effect of change in LULC on rainfall forecast quantitatively. IMD gridded rainfall data having a horizontal resolution of $0.25^{\circ}\times0.25^{\circ}$ is used to verify the rainfall forecast over the Indian continent. The gridded data was prepared using IMD archived daily rainfall data measured by rainfall gauge stations spread across India (Pai et al. 2014). Both observed and forecast data are brought to a common grid of $0.25^{\circ}\times0.25^{\circ}$ resolution before comparison. In addition, the *“European Center for Medium Range Weather Forecasting re-analysis (ERA) interim”* analyses at

~14 km resolution is used for spatial verification of the surface meteorological parameters. Before the statistical verification, the model forecasts are brought to the ERA interim grid resolution. In this study, bilinear interpolation is used to bring the model forecast to the grid resolution.

Bias and RMSE (Root Mean Square Error) are the two skill scores and statistical measures such used for spatial verification. RMSE is one of the standard quantitative and statistical method to estimate the accuracy of a model. It is the squared root of the average of the square of forecast (X_i) departure from the observation (O_i) as shown in equation (1.1):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - X_i)^2} \qquad (1.1)$$

where $i = 1, \dots\dots, N$ is the number of forecasts and N, which is 30 in this case is the total number of forecasts from each experiment for the whole month of July. Smaller the values of RMSE, better is the model performance.

The mean bias (ME), also known as BIAS is the average forecast departure from observations as shown in equation (1.2):

$$BIAS = \frac{1}{N}(O_i - X_i) \qquad (1.2)$$

It ranges from $-\infty$ to ∞ and the perfect score is zero. Negative bias shows overestimation by model forecast and positive bias directs underestimation by model forecast. In this study, NCL language is used for data visualization and analysis. NCL (NCAR Command Language) is an interpreted language which is intended specifically for scientific data analysis and visualization.

CHAPTER 4: RESULT & DISCUSSIONS

4.1 Results:

In this section, the performances of the experiments namely USGS, MODIS and ISRO during the Indian summer monsoon (ISM) are evaluated.

4.1.1 LULC analysis over NER:

The LULC classes for the three experiments are shown in Figure 5. For better analysis, the LULC classes are divided into 10 significant categories over NER. It is observed that there is a remarkable difference in ISRO LULC map in comparison to the other experiments around the Brahmaputra River and valley region which is also one of the main floods plain of NER. ISRO LULC shows a mixture of Cropland, Grassland and Forest over this region. However, the same representation is not observed for the other two experiments where more Cropland is shown by USGS and MODIS. From Figure 5, it is clearly perceived that the area near river side mostly consists of Grassland in ISRO LULC whereas USGS shows mostly Cropland and MODIS shows unclassified category. Over the Meghalaya region which is also the highest rainfall region of India, MODIS shows mostly Savanna LULC class which is not the same for ISRO and USGS. The Savanna category is only noticed in MODIS LULC class over NER. Shrubland is also one such category that is visible only in ISRO LULC to the southern and eastern region of NER. The key objective of the present research work is to evaluate the impact of these changes over the rainfall forecast for the same region.

4.1.2 Validation of Rainfall over NER India:

The spatial distribution of observed IMD gridded rainfall is shown in Figure 6a. It displays the monthly mean rainfall for July 2018 which clearly shows highest rainfall zone over Meghalaya and the other two significant rainfall zone are around the Brahmaputra valley which is also spread over Arunachal Pradesh, Manipur and Sikkim and southern part of NER. The simulation of 24 hour forecast of total rainfall averaged over the entire month of July 2018 are compared with the observed rainfall and it is derived that all the three experiments are able to demonstrate the pattern of rainfall distribution fairly well, however marginally large bias of rainfall amount is observed (Figure not shown). The bias (Observed-Forecast) as observed from Figure 6b depicts that the underestimation of rainfall in central part of NER and which is also near the Brahmaputra valley as simulated by USGS is reduced to some extent by ISRO (Figure 6c). More underestimation is observed in MODIS as shown in Figure 7a. It is important to mention here that it is the same area where the LULC representation of ISRO is different from the rest of the LULC data which suggests more contribution to rainfall LULC change.

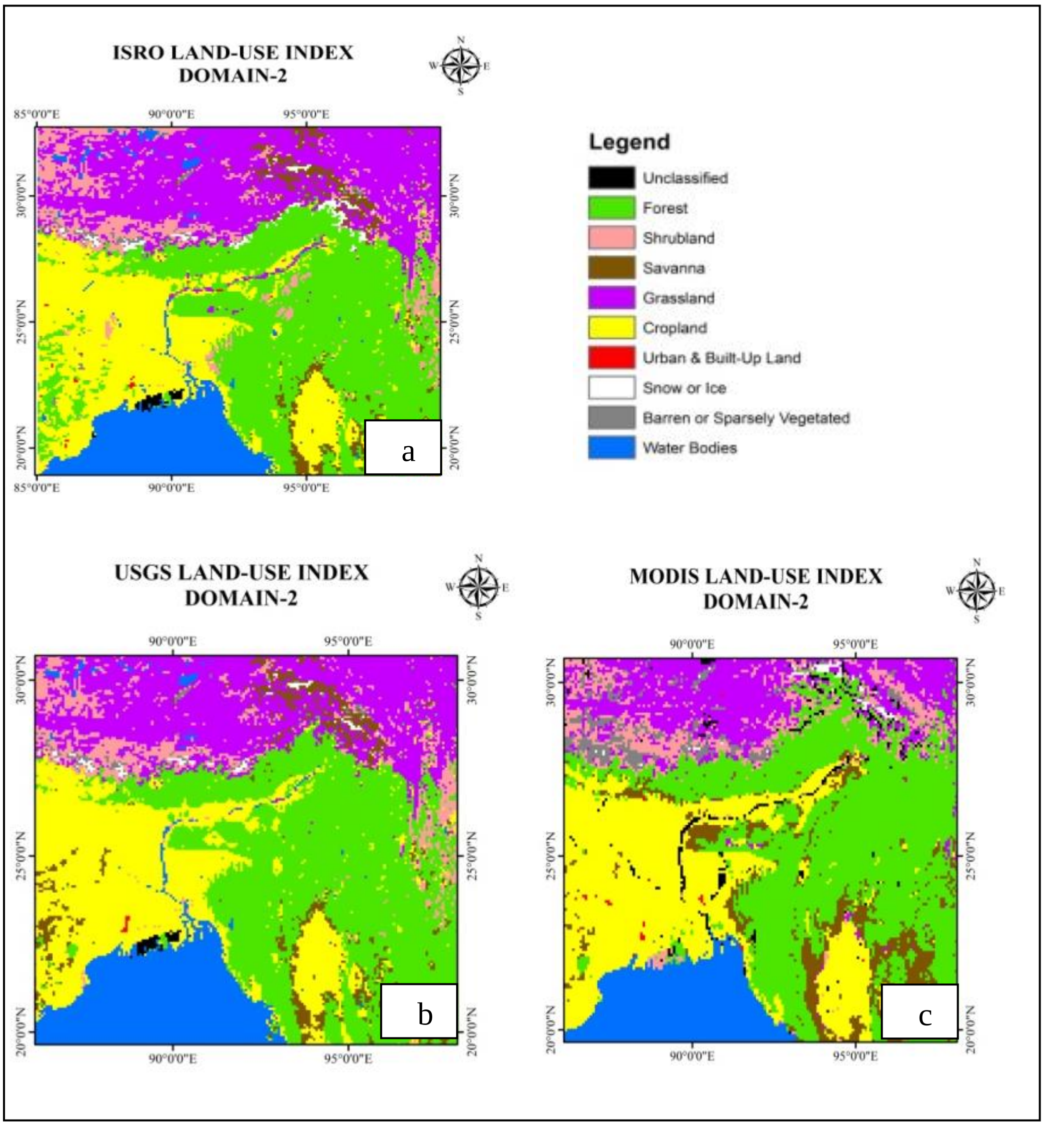


Figure 5: LULC Map of North-Eastern region of India with 10 classes from (a) ISRO, (b) USGS and (c) MODIS.

However, the mean error or BIAS does not measure the magnitude of the error. Therefore, to gain some comprehensive outcome RMSE for all the experiments are calculated. The RMSE plots also depict the same result where it is observed that the RMSE in USGS (Figure 6d) and MODIS (Figure 7c) experiments is significantly reduced in ISRO (Figure 6e, 7d) experiment for central, southern and eastern part of NER. Not much improvement is observed over Meghalaya. The major objective of this study is ascertained by the results that represents the positive impact of updated high resolution LULC data on rainfall forecast.

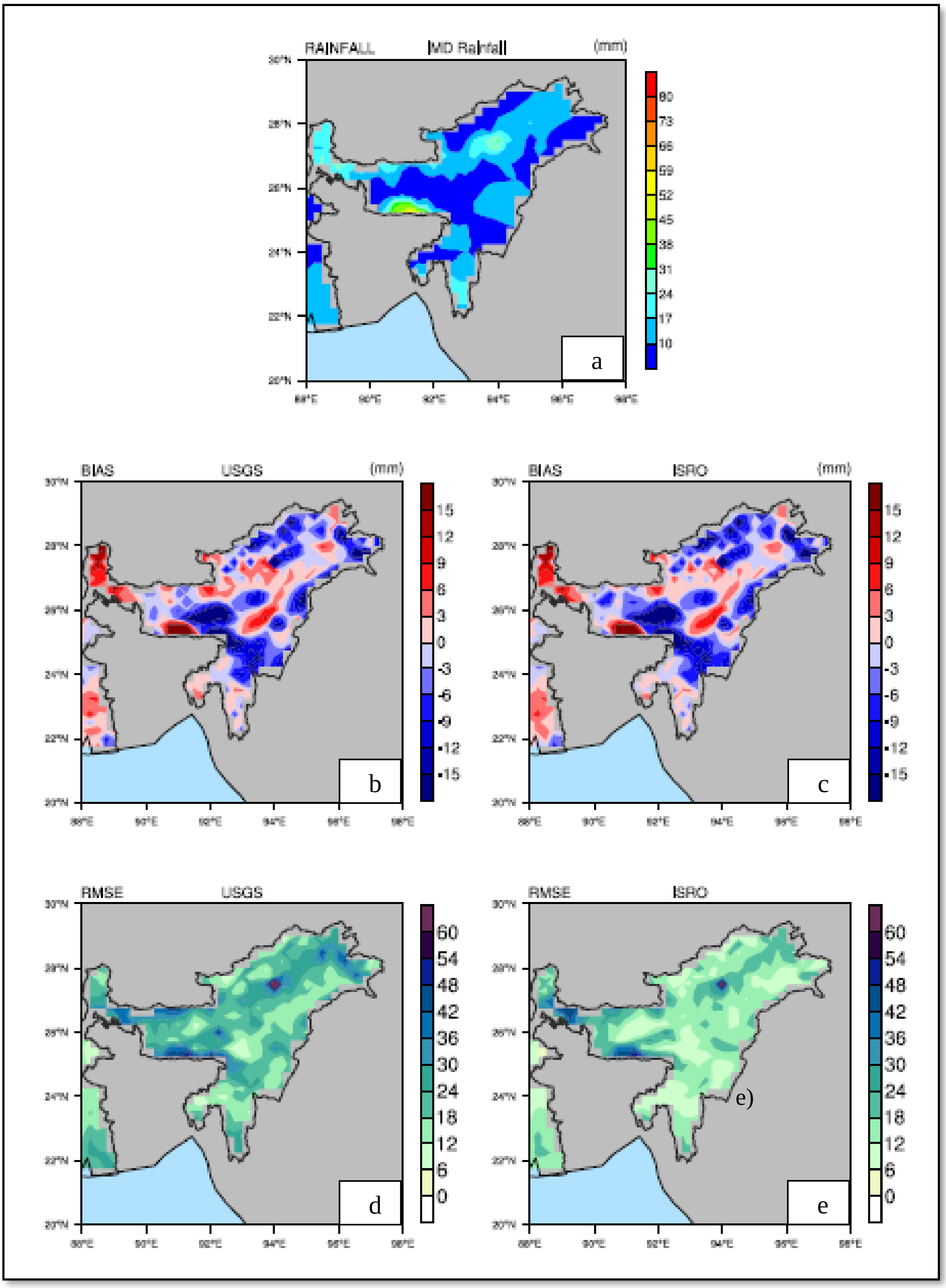


Figure 6: (a) Observed spatial distribution of monthly averaged (July) 24 h accumulated rainfall (mm/day) and BIAS in forecasted rainfall from (b) USGS (c) ISRO. RMSE in forecasted rainfall from (d) USGS and (e) ISRO

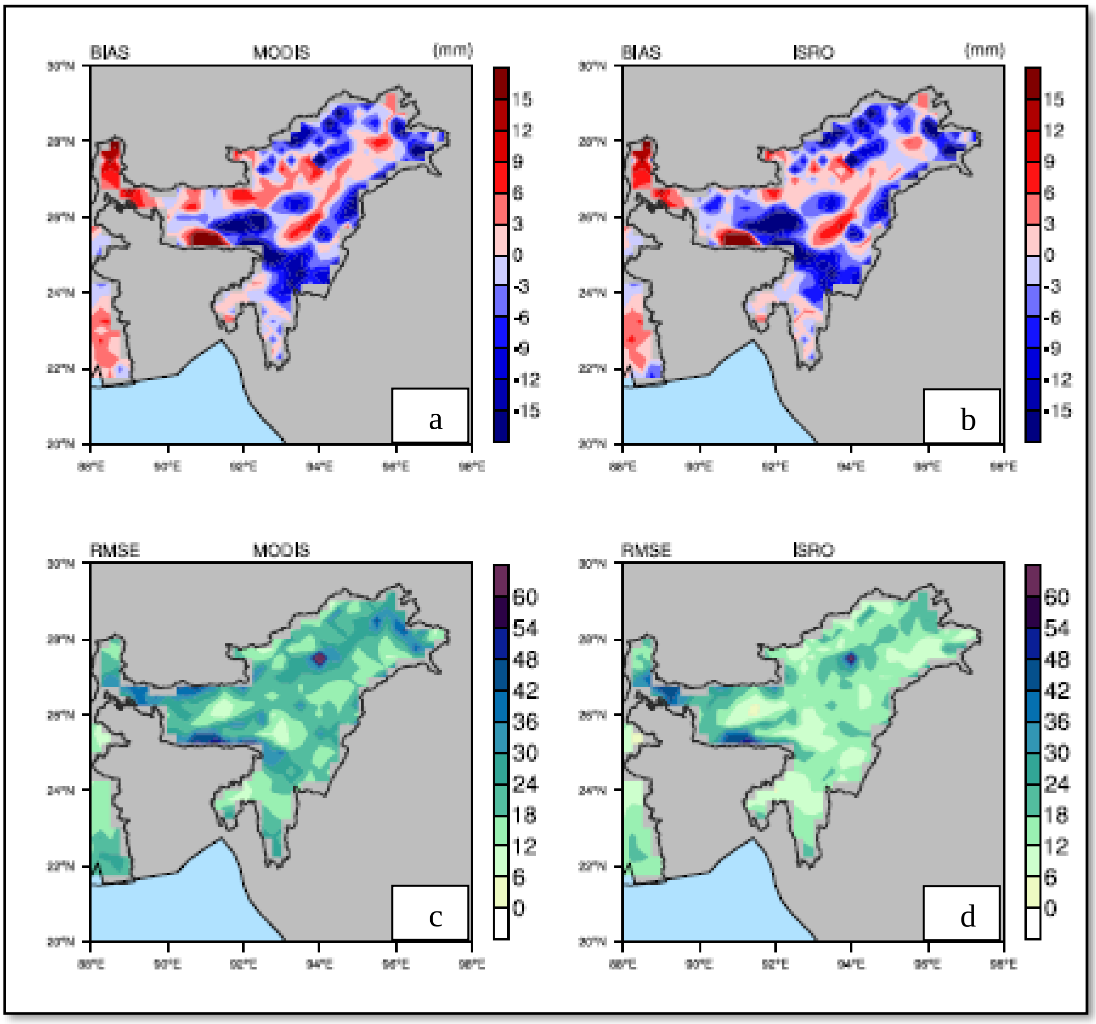


Figure 7: BIAS in forecasted rainfall from (a) MODIS (b) ISRO. RMSE in forecasted rainfall from (c) MODIS and (d) ISRO

4.1.3 Validation of Surface Temperature and Dew Point Temperature:

It has been found in many studies that temperature and precipitation are physically related to one another and their relationship strongly depends on region and season (Isaac and Stuart, 1992; Zhao and Khalil, 1993; Wu, 2014). Rajeevan et al. investigated the temporal relationship between land surface temperature and rainfall for Indian summer monsoon , where rainfall and temperature are found to be positively correlated during the month January and May but negatively correlated for the month of July. Figure 8a depicts the spatial distribution of surface temperature in July 2018 as collected from ERA Interim re-analysis data. It is observed from Figure 8b, c that surface temperature is overestimated by both USGS and MODIS around the Brahmaputra river side with more overestimation by MODIS. The overestimation is significantly reduced by ISRO (Figure 8d) where the LULC category is mostly Grassland which is different from USGS and MODIS. No such significant impact is observed over other parts of NER. The same results are obtained from the RMSE plots as shown in Figure8e-f. The inappropriate classification of LULC by MODIS and USGS may be the reason for overestimation of temperature and underestimation of rainfall over the same region.

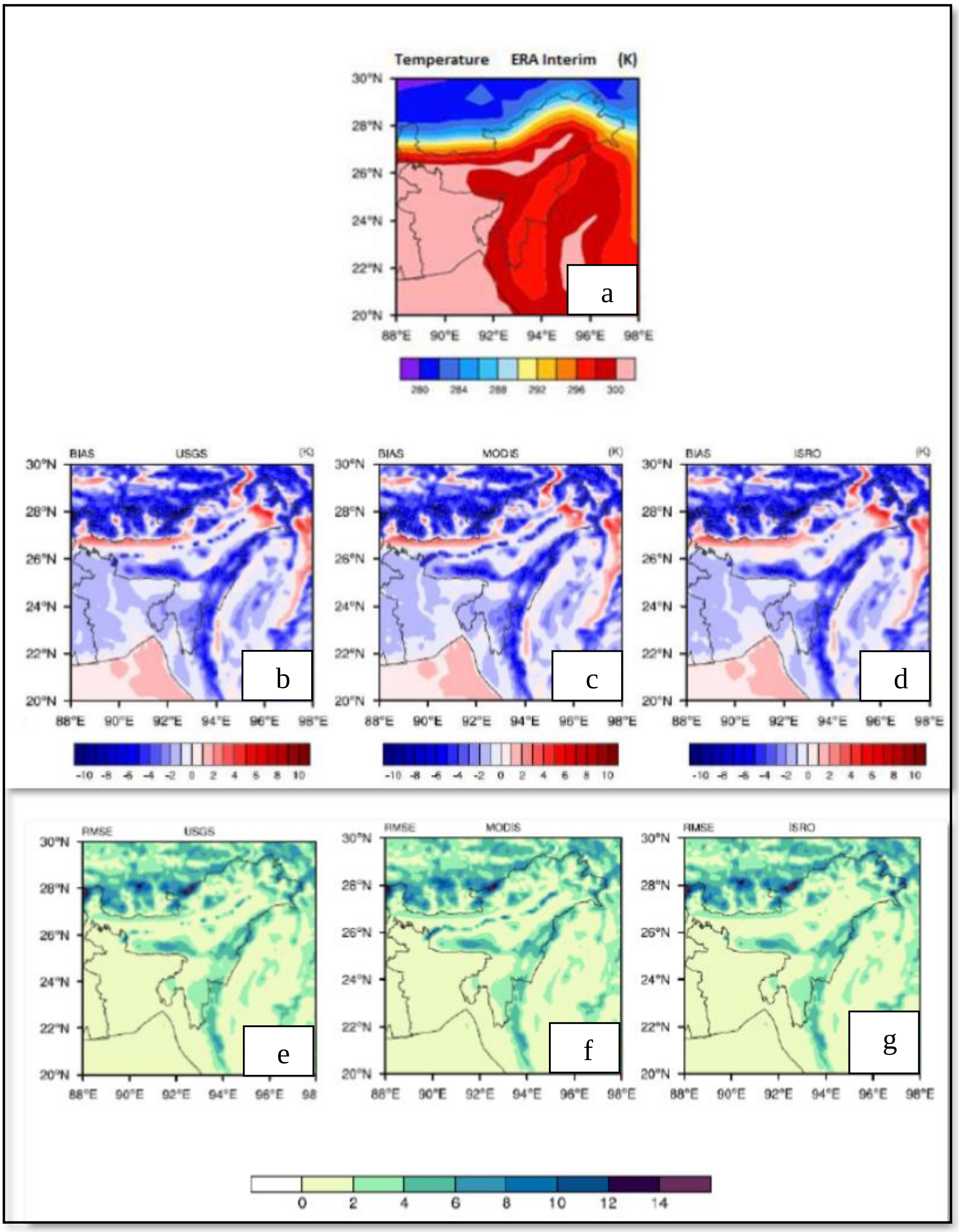


Figure 8: Monthly averaged surface temperature from (a) ERA interim and BIAS in 24 hour forecast temperature from (b) USGS, (c) MODIS and (d) ISRO and RMSE from (e) USGS, (f) MODIS and (g) ISRO

Generally, monsoon season is referred as the period of very high humidity and relative humidity can be inferred from dew point values. Figure 9b-d shows the RMSE of model simulated dew point temperature with respect to ERA Interim data where it is observed that over the same Brahmaputra region the error of USGS and MODIS are more than ISRO. It can be inferred from the results that there is significant impact of land use change on meteorological parameters.

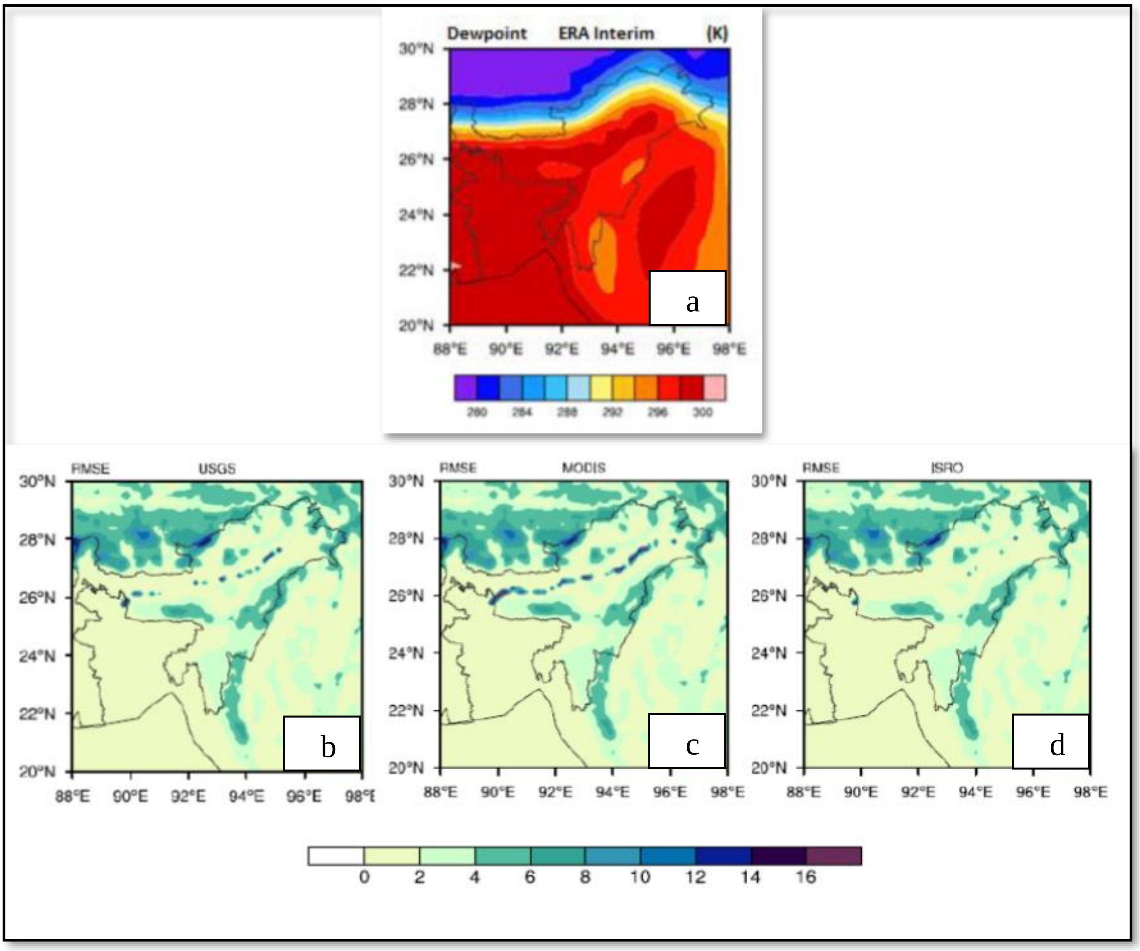


Figure 9: Monthly averaged surface dew point temperature from (a) ERA interim and RMSE in 24 hour forecast dew point temperature from (b) USGS, (c) MODIS and (d) ISRO

4.1.4 Validation of Surface wind:

Surface wind is another parameter which is affected by large scale circulation as well as LULC changes. Figure 10a shows the ERA Interim monthly mean surface wind and Figure 10b-d shows the RMSE of model simulated surface wind with respect to ERA Interim reanalysis data. There is a significant decrease in RMSE of ISRO and USGS in comparison to MODIS in Meghalaya and its adjacent area. MODIS classified this region as Savanna whereas the same region is classified as Forest by USGS and ISRO. Savanna is a land use type characterised by widely spread trees whereas Forest is characterised by dense trees. This major difference in land use type contributes towards overestimated wind speed in this region by MODIS.

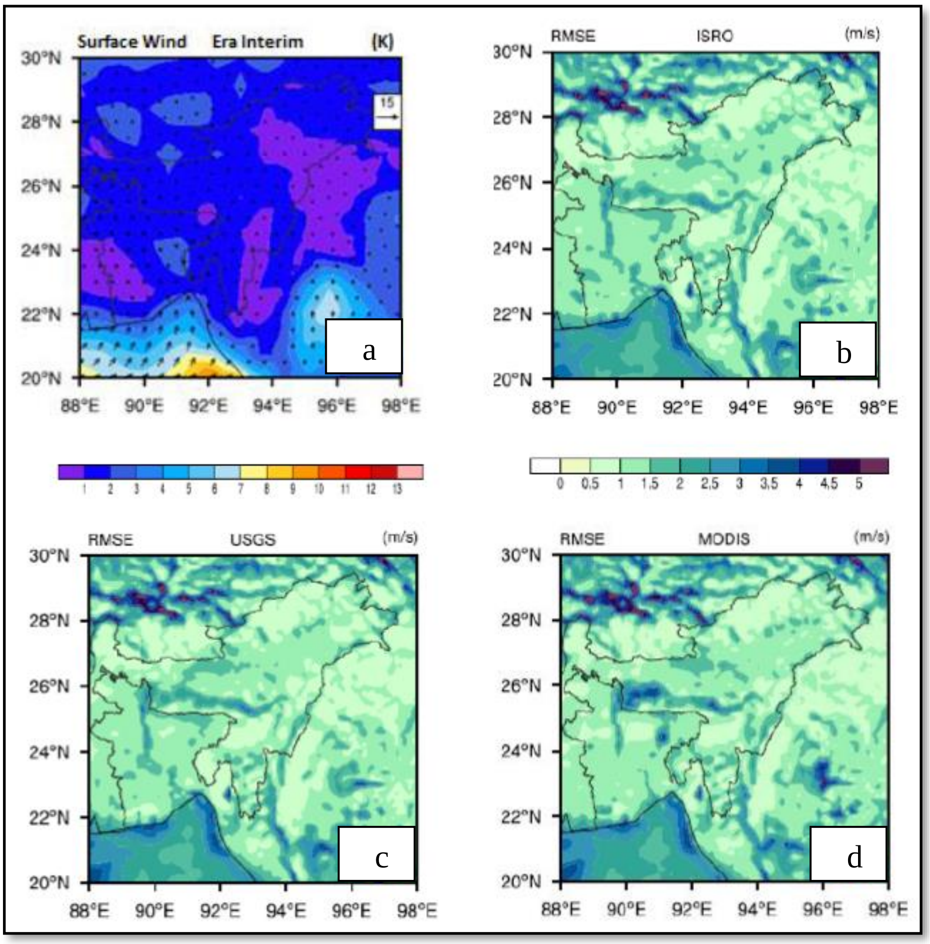


Figure 10: Monthly averaged surface wind from (a) ERA interim and RMSE in 24 hour forecast surface wind from (b) ISRO, (c) USGS and (d) MODIS

CHAPTER 5: CONCLUSION

The key aim of this project is to evaluate the impacts of change in land use and land cover on rainfall forecast over the North-Eastern region of India using Weather Research and Forecasting model. The WRF model is a physical based model, ensuring that the simulations will be more illustrative and representative of the complex processes than any other quantitative methods.

As a consequence of the extreme meteorological complexities intricate in simulating and forecasting the incidence of heavy rainfall over such a tropical region; use of the WRF modelling method in a nested configuration has been selected for the present research work. The performance of the WRF model for the one-month simulation specifically over North-Eastern at 9 km resolution has been studied for three different LULC data namely USGS, MODIS, ISRO-AWiFS.

The results suggest that the high resolution and updated LULC data obtained from ISRO has the potential to improve biases of the rainfall forecast over the North-Eastern region (NER) of India mainly around the central and western part of Assam covering the Brahmaputra valley and the RMSE results reveals the significant improvement by ISRO LULC data almost all over NER. It is also evident from the result that the LULC changes also impact the rainfall forcing meteorological parameters for instance surface temperature and dew point temperature again over the same Brahmaputra river side. The LULC category over the Brahmaputra river side is mostly Grassland for ISRO data which is different for USGS and MODIS. However, improved surface wind is mostly observed over Meghalaya region for ISRO as well as USGS in comparison to MODIS. It is important to mention here that the LULC over this area as shown by MODIS is Savana whereas USGS and ISRO depict it as Forest. Since, LULC is the only parameter which has been changed for the experiments, so the changes of LULC can be considered as the prime reason for the effect on the meteorological parameters. All the results reveal the significant impact of updated high resolution ISRO LULC data on the forecast of rainfall and the associated meteorological parameters.

REFERENCES

Biswadip Gharali, Technical Report, NRSC, ISRO, 2014: IRS-P6 AWiFS Derived Gridded Land Use/Land Cover Data Compatible to Mesoscale Models (MM5 and WRF) Over Indian Region

Bramer, David; Hall, Steven B.; Wojtowicz David, 2010. *Dew Point and Temperature- WW2010.* [Online] Available at: http://ww2010.atmos.uiuc.edu/(Gh)/guides/maps/upa/dewp.rxml [Accessed 10 05 2020].

Chang, H.-I., Kumar, A., Niyogi, D. & Dudhia, J., 2009. The role of land surface processes on the mesoscale simulation of the July 26, 2005 heavy rain event over Mumbai, India. *Global and Planetary Change,* 67(1), pp. 87-103.

Chevuturi, A. & Dimri, A. P., 2016. Investigation of Uttarakhand (India) disaster-2013 using weather research and forecasting model. *Natural Hazards,* 82(3), pp. 1703-1726.

Chevuturi, A. et al., 2015. Numerical simulation of an intense precipitation event over Rudraprayag in the central Himalayas during 13–14 September 2012. *Journal of Earth System Science,* 124(7), pp. 1545-1561.

Collins, M. et al., 2013. Observational challenges in evaluating climate models. *Nature Climate Change,* 3(11), pp. 940-941.

Cong, R.-. G. & Brady, M., 2012. The Interpendence between Rainfall and Temperature: Copula Analyses. *The Scientific World Journal,* pp. 1-11.

Das, S. et al., 2008. Skills of different mesoscale models over Indian region: Forecast errors. *Journal of Earth System Science.,* Volume 117, pp. 603-620.

Deb, S. K., Srivastava, T. P. & Kishtawal, C., 2008. The WRF model performance for the simulation of heavy precipitating events over Ahmedabad during August. *Journal of Earth System Science,* 117(5), pp. 589-602.

Dikshit, K. R. & Dikshit, J. K., 2014. *North-East India: Land, People and Economy.* s.l.:s.n.

Dimri, A. P. et al., 2016. A review of atmospheric and land surface processes. *Science of the Total Environment,* Volume 556, pp. 98-115.

Ebert, E. E., Janowiak, J. E. & Kidd, C., 2007. Comparison of Near-Real-Time Precipitation Estimates from Satellite Observations and Numerical Models. *Bulletin of the American Meteorological Society,* 88(1), pp. 47-64.

Gadgil, S. & Sajani, S., 1998. Monsoon precipitation in AMIP runs. *Climate Dynamics,* 14(9), pp. 659-689.

Grossman-Clarke, S., Zehnder, J. A., Loridan, T. & Grimmond, C. S. B., 2010. Contribution of Land Use Changes to Near-Surface Air Temperatures during Recent Summer Extreme Heat Events in the Phoenix Metropolitan Area. *Applied Meteorology and Climatology,* 49(8), pp. 1649-1664.

Gsella, A., Meij, A. d., Kerschbaumer, A. & Reimer, E., 2014. Evaluation of MM5, WRF and TRAMPER meteorology over the complex terrain of the Po Valley, Italy. *Atmospheric Environment,* Volume 89, pp. 797-806.

Hazra, A., Chaudhari, H. S., Ranalkar, M. & Chen, J.-P., 2017. Role of interactions between cloud microphysics, dynamics and aerosol in the heavy rainfall event of June 2013 over Uttarakhand, India. *Quarterly Journal of the Royal Meteorological Society,* 143(703), pp. 986-998.

Hong, S. et al., 2009. Effects of vegetation and soil moisture on the simulated land surface processes from the coupled WRF/Noah model. *Journal of Geophysical Research*, 114(D18), pp. 1-13.

Jianjun, H. et al., 2014. Impact of land surface information on WRFs performance in complex terrain area. *Chinese Journal of Atmospheric sciences,* Volume 38, pp. 484-404.

Jim, A. B. & Sistach, M. U., 2004. Land use influence in WRF model .. *A high resolution mesoscale modeling over Oriental Pyrenees..*

Jin, J., Miller , N. L. & Schlegel, N., 2010. Sensitivity Study of Four Land Surface Schemes in the WRF Model. *Advances in Meterology,* pp. 185-194.

Kotal, S. D., Roy, S. S. & Bhowmik, S. R., 2014. Catastrophic heavy rainfall episode over Uttarakhand during 16-18 June 2013 - observational aspects. *Current science,* 107(2), pp. 234-245.

Kumar, A., Dudhia, J., Rotunno, R. & Niyogi, D., 2008. Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF) model. *Quarterly Journal of the Royal Meteorological Society,* 134(636), pp. 1897-1910.

Kumar, A., Houze Jr., R. A., Rasmussen, K. L. & Peters-Lidard, C., 2014. Simulation of a Flash Flooding Storm at the Steep Edge of the Himalayas. *Journal of Hydrometeorology,* 15(1), pp. 212-228.

Kumar, S. M. et al., 2012. Numerical simulation of cloud burst event on August 05, 2010, over Leh using WRF mesoscale model. *Natural Hazards,* 62(3), pp. 1261-1271.

Li , J., Zheng, X., Zhang, C. & Chen, Y., 2018. Impact of Land-Use and Land-Cover Change on Meteorology in the Beijing–Tianjin–Hebei Region from 1990 to 2010. *Sustainability* , 10(1), pp. 1-22.

Litta, A. J., Mohanty, U. C., Das, S. & Idicula, S. M., 2012. Numerical simulation of severe local storms over east India using WRF-NMM mesoscale model. *Atmospheric Research,* Volume 116, pp. 161-184.

Madala, S., Satyanarayana, A. V. & Rao, T. N., 2014. Performance Evaluation of PBL and Cumulus Parameterization Schemes of WRF-ARW Model in Simulating Severe Thunderstorm Events over Gadanki MST Radar Facility – Case study. *Atmospheric Research,* Volume 139, pp. 1-17.

Mahmood, R., Leeper, R. & Quintanar, A. I., 2011. Sensitivity of Planetary Boundary Layer Atmosphere to Historical and Future Changes of Land use/land cover, Vegetation Fraction, and Soil Moisture in Western Kentucky, USA. *Global and Planetary Change,* 78(1-2), pp. 36-53.

Medina, S., Houze Jr, R. A., Kumar, A. & Niyogi, D., 2010. Summer monsoon convection in the Himalayan region: Terrain and land cover effects. *Quarterly Journal of the Royal Meteorological Society,* 136(648), pp. 593-616.

Medisetti Bhavana, G. K. P. P. K. A. S. K. J. G., 2018. EVALUATION OF HIGH RESOLUTION URBAN LULC FOR SEASONAL FORECASTS OF URBAN CLIMATE USING WRF MODEL. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Volume Volume IV-5, pp. 303 - 310.

Meyer, D. W., 1993. The Basics of Weather Models,. *Air Weather Service Scoot AFB IL.,* Volume No. AWS/FM-93/001/..

Mitra, A. K. et al., 2013. Gridded daily Indian monsoon rainfall for 14 seasons: Merged TRMM and IMD gauge analyzed values. *Journal of Earth System Science,* Volume 122, No. 5, pp. 1173-1182.

Mohanty, U. C., Routray, A., Osuri, K. K. & Siripurapu, K. P., 2012. A Study on Simulation of Heavy Rainfall Events Over Indian Region with ARW-3DVAR Modeling System. *Pure and Applied Geophysics,* 169(3), pp. 381-399.

Osuri, K. K., Nadimpalli, R., Mohanty, U. C. & Niyogi, D., 2017b. Prediction of rapid intensification of tropical cyclone Phailin over the Bay of Bengal using the HWRF modelling system. *Quarterly Journal of the Royal Meterological Society,* 143(703), pp. 678-690.

Osuri, K. K. et al., 2017a. Improved prediction of severe thunderstorms over the Indian Monsoon region using high-resolution soil moisture and temperature initialization. *Scientific Reports,* Volume 7.

Osuri, K. K. et al., 2017. Improved prediction of severe thunderstorms over the Indian Monsoon region using high-resolution soil moisture and temperature initialization. *Scientific Reports,* Volume 7, pp. 1-12.

Prakash, S. et al., 2014. Seasonal intercomparison of observational rainfall datasets over India during. *International Journal of Climatology, ,* 35(9), pp. 2326-2338.

Rajesh, P. V. et al., 2016. Role of land state in a high resolution mesoscale model for simulating the Uttarakhand heavy rainfall event over India. *Journal of Earth System Science,* Volume 125, pp. 475-498.

Raju, P. V., Potty, J. & Mohanty, U. C., 2011. Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model. *Meteorology and Atmospheric Physics 113(3):125-137,* 113(3), pp. 125-137.

Ratna, S. B., Sikka, D. R., Dalvi, M. & Ratnam, J. V., 2011. Dynamical simulation of Indian summer monsoon circulation, rainfall and its interannual variability using a high resolution atmospheric general circulation model. *International Journal of Climatology,* 31(13), pp. 1927-1942.

Ravindranath, M., R., A. & Bohra, A. K., 2010. *Experimenton utilization of AWiFS LU/Lc data in WRF mesoscale model,* s.l.: NMRF/RR/1/2010.

Rossa, A. et al., 2010. Rossa, A., Haase, G., Keil, C., Alberoni, P., BaPropagation of uncertainty from observing systems into NWP: COST-731 Working Group 1. *Atmospheric Science Letters,* Volume 11, p. 145–152..

Routray, A., Mohanty, U. C., Niyogi, D. & Rizvi, S., 2009. Simulation of heavy rainfall events over Indian monsoon region using WRF-3DVAR data assimilation system. *Meteorology and Atmospheric Physics,* 106(1), pp. 107-125.

Routray, A. et al., 2016. Impact of Satellite Radiance Data on Simulations of Bay of Bengal Tropical Cyclones Using the WRF-3DVAR Modeling System. *IEEE Transactions on Geoscience and Remote Sensing,* Volume 54, pp. 2285-2303.

Roy, A. et al., 2018. INTERCOMPARISON OF DIFFERENT RAINFALL PRODUCTS AND VALIDATION OF WRF MODELLED RAINFALL ESTIMATION IN N-W HIMALAYA DURING MONSOON PERIOD. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences.,* Volume IV-5(10.5194/isprs-annals-IV-5-351-2018.), pp. 351-358.

Scoones, I., 1991. Wetlands in drylands: key resources for agricultural and pastoral production in Africa. *Ambio,* 20(8), pp. 366-371.

Shekhar, M. S. et al., 2015. A study on the heavy rainfall event around Kedarnath area (Uttarakhand) on 16 June 2013. *Journal of Earth System Science,* 124(7), pp. 1531-1544.

Skamarock, W. C. et al., 2005. *A Description of the Advanced Research WRF Version 2,* s.l.: University Corporation for Atmospheric Research.

Skamarock, W. C. et al., 2008. *A Description of the Advanced Research WRF Version 3,* s.l.: University Corporation for Atmospheric Research.

Srinivas, C. V. et al., 2012. Simulation of the Indian summer monsoon regional climate using advanced research WRF model. *International Journal of Climatology,* 33(6), pp. 1195-1210.

Thayyen, R., Dimri, A. P., Kumar, P. & Agnihotri, P., 2013. Study of cloudburst and flash floods around Leh, India during August 4-6, 2010. *Natural Hazards,* 65(3), pp. 2175-2204.

Trenberth, K. E., Stepaniak, D. P. & Caron, J. M., 2000. The Global Monsoon as Seen through the Divergent Atmospheric Circulation. *Journal of Climate,* Volume 13, pp. 3969-3993.

Turner, A. G. & Annamalai, H., 2012. Climate change and the South Asian summer monsoon. *Nature Climate Change,* 2(8), pp. 587-595.

Vaidhya, S. S. & Kulkarni, J. R., 2007. Simulation of heavy precipitation over Santacruz, Mumbai on 26 July 2005, using Mesoscale model. *Meteorology and Atmospheric Physics,* 98(1), pp. 55-66.

Vellore, R. K. et al., 2016. Monsoon-extratropical circulation interactions in Himalayan extreme rainfall. *Climate Dynamics*, 46(11-12), pp. 3517-3546.

Wang, K., Xiong, Z. & Yan, X., 2015. Modeling the climatic effects of the land use/cover change 637 in eastern China. *Physics and Chemistry of the Earth,* Volume 87, pp. 97-107.

Wessels, W., 2018. *What Is Dew Point And How Does It Affect The Weather, Especially Rainfall?.* [Online] Available at: https://ownyourweather.com/what-is-dew-point/[Accessed 10 05 2020].

Yu, W., Nakakita, E. & Jung, K., 2016. Flood Forecast and Early Warning with High-Resolution Ensemble Rainfall from Numerical Weather Prediction Model.. *Procedia Engineering,* Volume 154, pp. 498-503.

Zhang, N., Gao, Z., Wang, X. & Chen, Y., 2010. Modeling the impact of urbanization on the local and regional climate in Yangtze River Delta, China. *Theoretical and Applied Climatology*, 102(3-4), pp. 331-342.

ANNEXURE

Table 4: Geogrid configuration for domain.

parent_id	1,1,

parent_grid_ratio	1,3,
i_parent_start	1,78
j_parent_start	1,80
e_we	180, 184
e_sn	180, 184
geog_data_res	For MODIS 'modis_30s', For USGS & ISRO 'usgs_30s',
dx	27000,
dy	27000,
map_proj	'mercator',
ref_lat	21.00,
ref_lon	88.00,
truelat1	21.0,
truelat2	21.0,
stand_lon	88.0,

Table 5: Domain configuration for namelist. input

time_step	120		dx	27000	9000
time_step_fract_num	0		dy	27000	9000
time_step_fract_den	1		grid_id	1	2
max_dom	2		parent_id	0	1
e_we	180	184	i_parent_start	1	78
e_sn	180	184	j_parent_start	1	89
e_vert	30	30	parent_grid_ratio	1	3
p_top_requested	5000		parent_time_step_ ratio	1	3
num_metgrid_levels	32		feedback	1	
num_metgrid_soil_levels	4		smooth_option	0	

Physics Options in WRF:

Table 6: Common physics options for land use lad cover simulations

mp_physics	6	6	isfflx	1	

ra_lw_physics	1	1	ifsnow	0	
ra_sw_physics	1	1	icloud	1	
radt	30	30	surface_input_source	3	
sf_sfclay_physics	1	1	num_soil_layers	4	
sf_surface_physics	2	2	num_land_cat	M-20	U/I-24
bl_pbl_physics	1	1	sf_urban_physics	0	0
bldt	0	0			
cudt	5	5			
cu_physics	1	1			