Urban-Scale Weather Modelling System for Prediction of Monsoon Heavy Rainfall Events over Indian Cities

U C Mohanty

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- Siksha “O” Anusandhan, Deemed to be University, Bhubaneswar for certain logistic facility

Overview

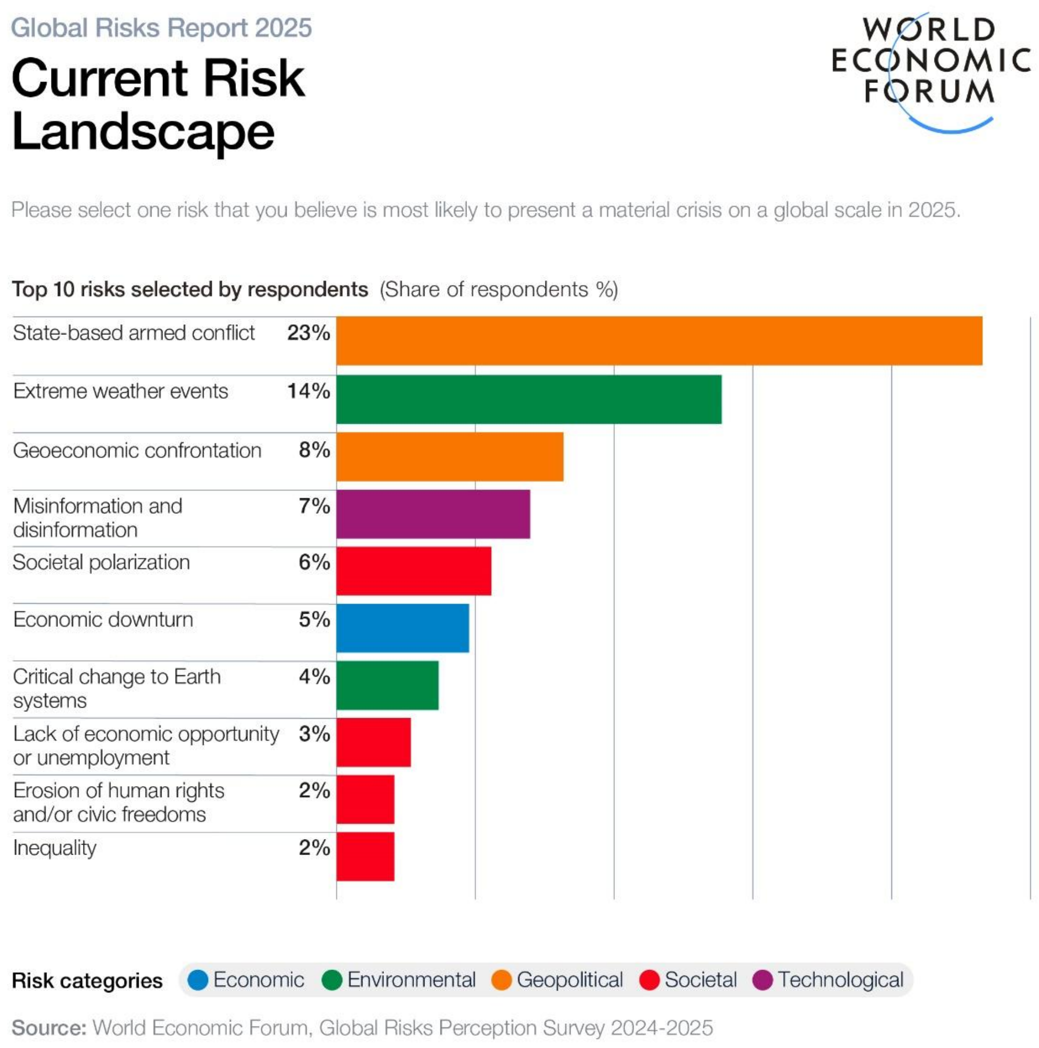
- Introduction
- Customization of uWRF model
- Simulation of 2022 heavy urban rainfall events
- Performance of operational uWRF model vs GFS
- Conclusions and Future scope

Introduction

- Monsoon extreme rainfall events (EREs) are increasing in frequency and intensity due to climate change, Anthropogenic emissions and urbanization effects, posing significant risks to infrastructure, agriculture, and livelihoods (e.g., Gowswami et al. 2006; Dash et al. 2009; Swain et al. 2023).

- Predicting EREs in urban areas remains a significant challenge due to complex land-atmosphere interactions, rapid urbanization, and the influence of localized convection, requiring high-resolution modeling and advanced forecasting techniques (Karrevula et al. 2024; Boyaj et al. 2025).

- Today, 55% of the world's population lives in urban areas, a projection that is expected to increase to 68% by 2050. (Source: https://www.un.org/)



Some Recent Impacts of EREs

with almost all areas of **Patna** under knee-deep waters and people struggling to meet their daily needs.

Gujarat's cultural capital **Vadodara** went under water for nearly 72 hours. 239 mm of rain in 24 hours from August 26 and 27, 2024

In the 2022 monsoon season, July turned out to be the wettest month in the city of **Hyderabad**. Source: https://scroll.in/

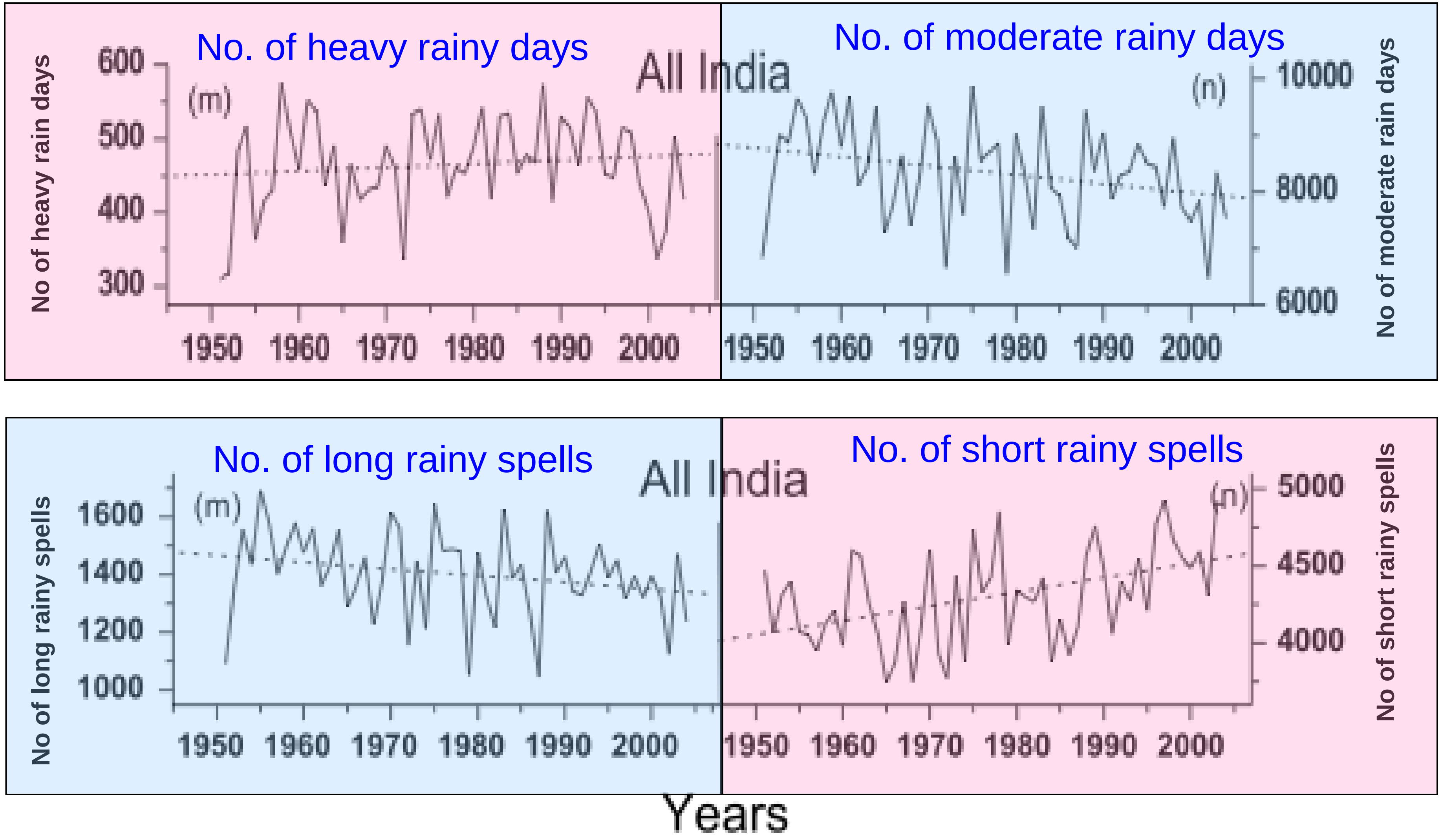
Some Recent Impacts of EREs

Two days of torrential rain have flooded **Bengaluru**, the southern city known as India's Silicon Valley, forcing tech workers to use boats and hitch rides on tractors to get to the office. September, 09, 2022. Source: https://www.hindustantimes.com/cities/bengaluru-news/

- India has faced more extreme weather events and higher damages in 2024 compared to past years.
- In 2024,these events claimed 3,238 lives, affected 3.2 million hectare of crops, destroyed 235,862 houses and buildings, and killed approximately 9,457 livestock.

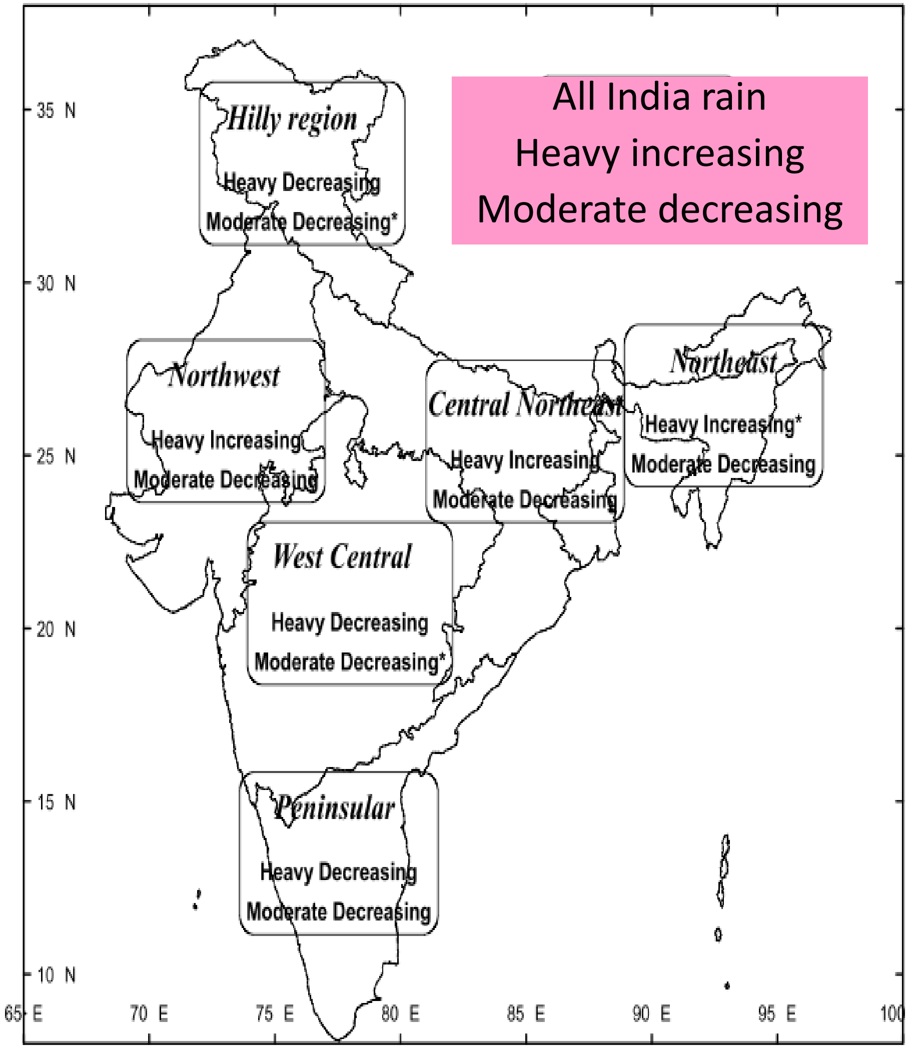
Source: https://www.newsclick.in/

Changes in the Frequency Distribution of heavy rainfall episodes during 1951-2007 in All-India Basis

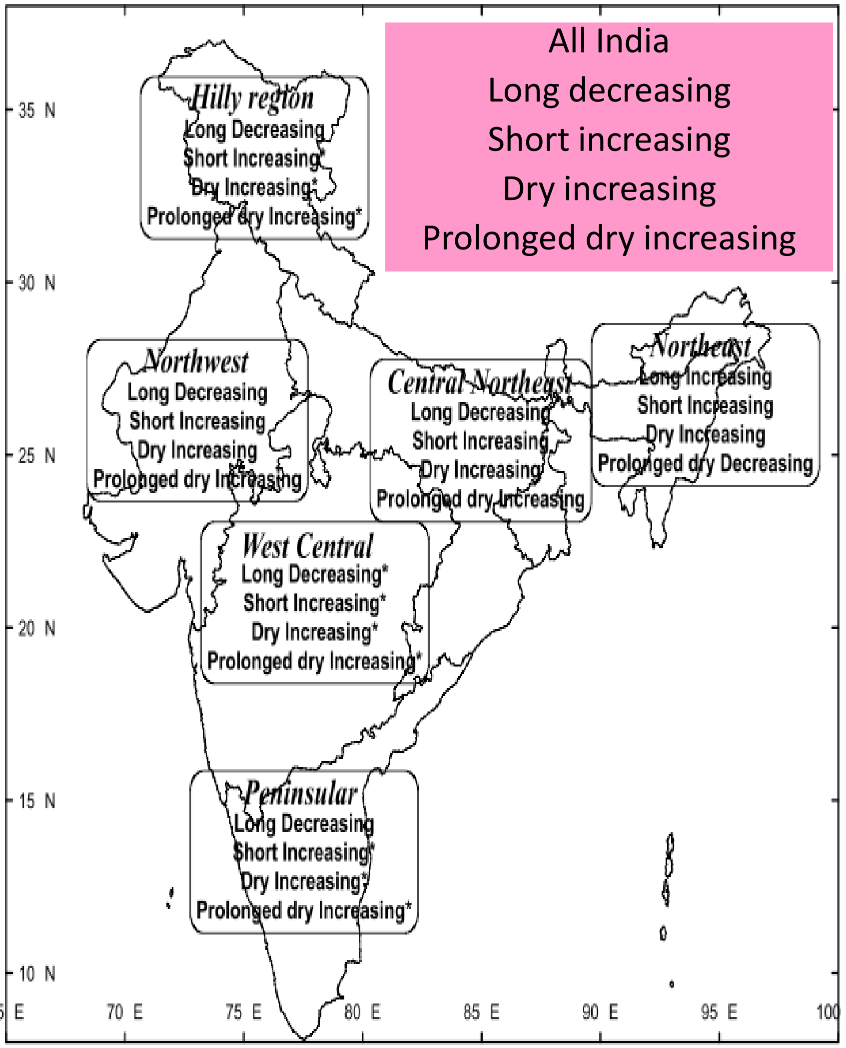


Dash, Kulakarni,Mohanty, & Prasad, 2009

Changes in patterns of Rain spells over Homogeneous regions of India



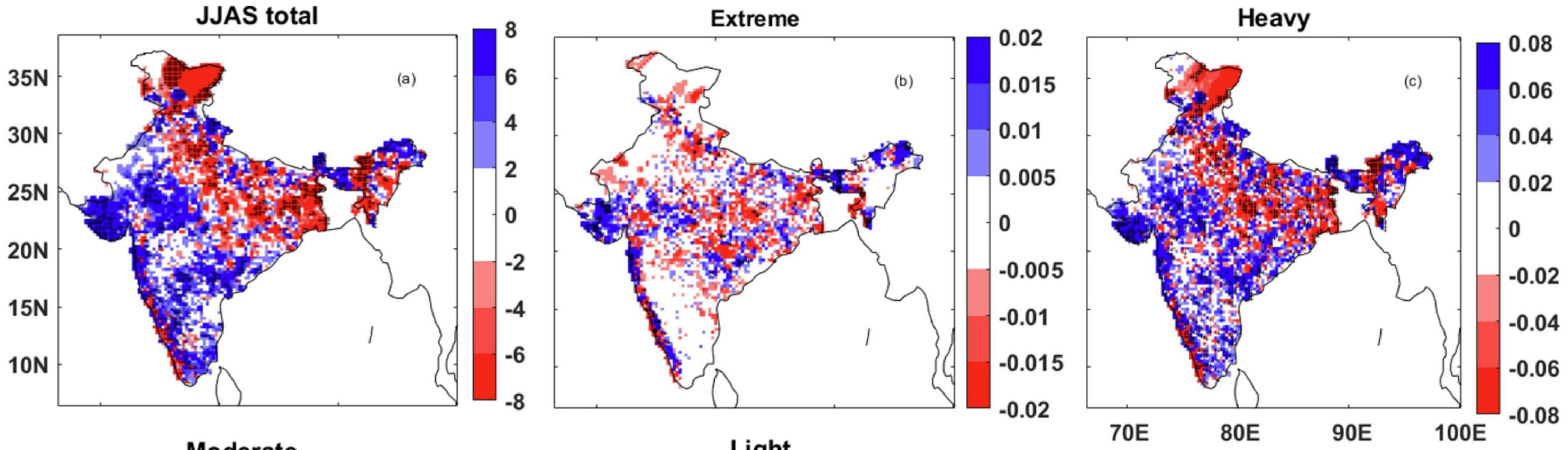
Heavy and moderate rain days occurring during the summer monsoon season in different regions.

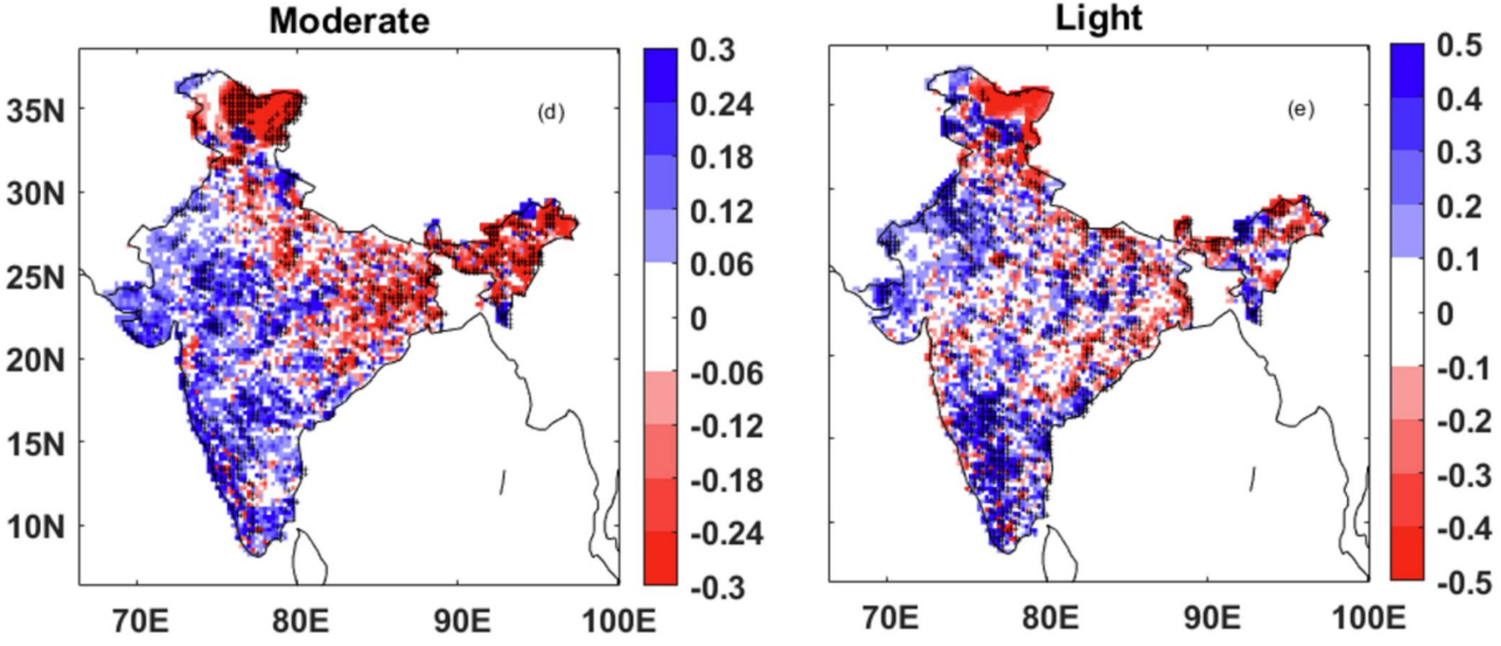


Long, short, dry, and prolonged dry spells of rainfall in different Indian regions for the monsoon season.

Dash, Kulakarni, Mohanty, & Prasad, 2009

Spatial distributions of temporal trends (mm/yr) (1991–2020)

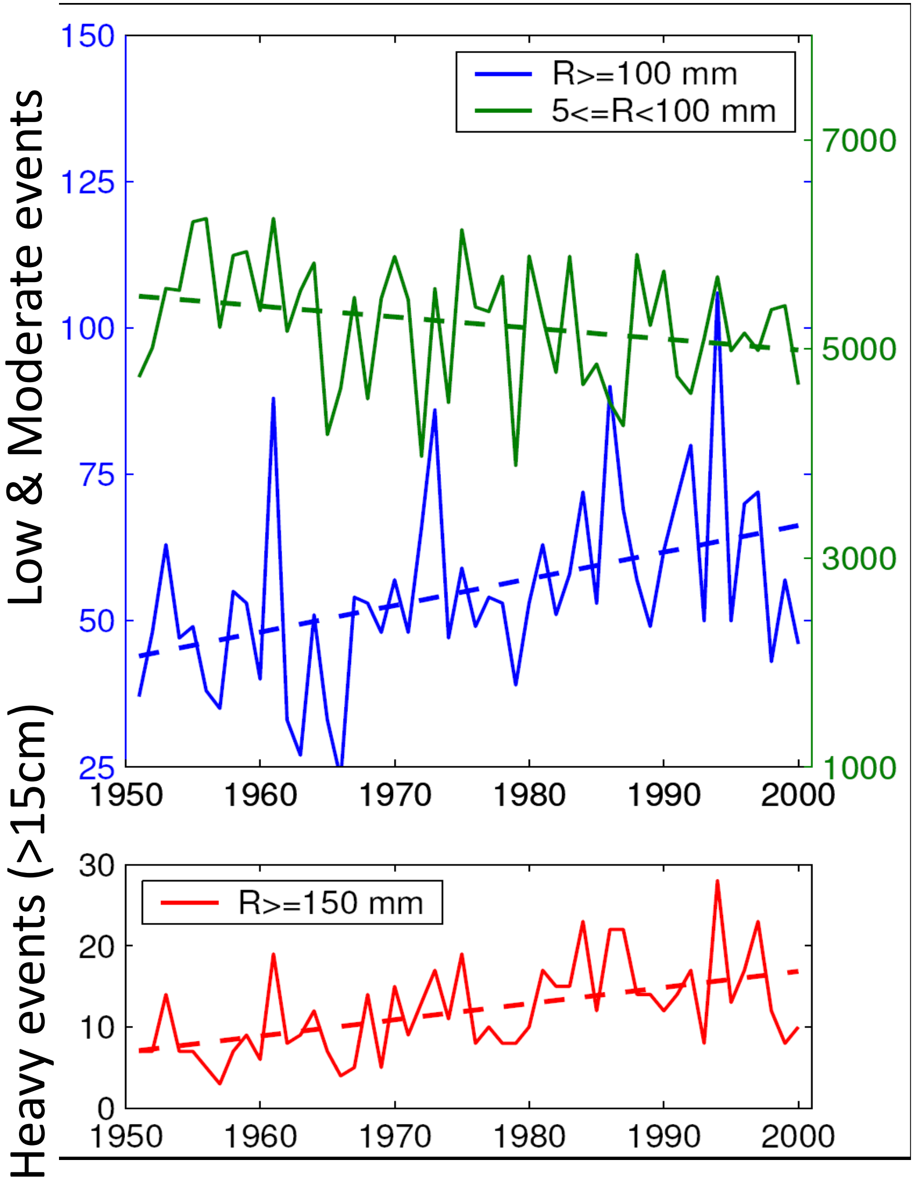




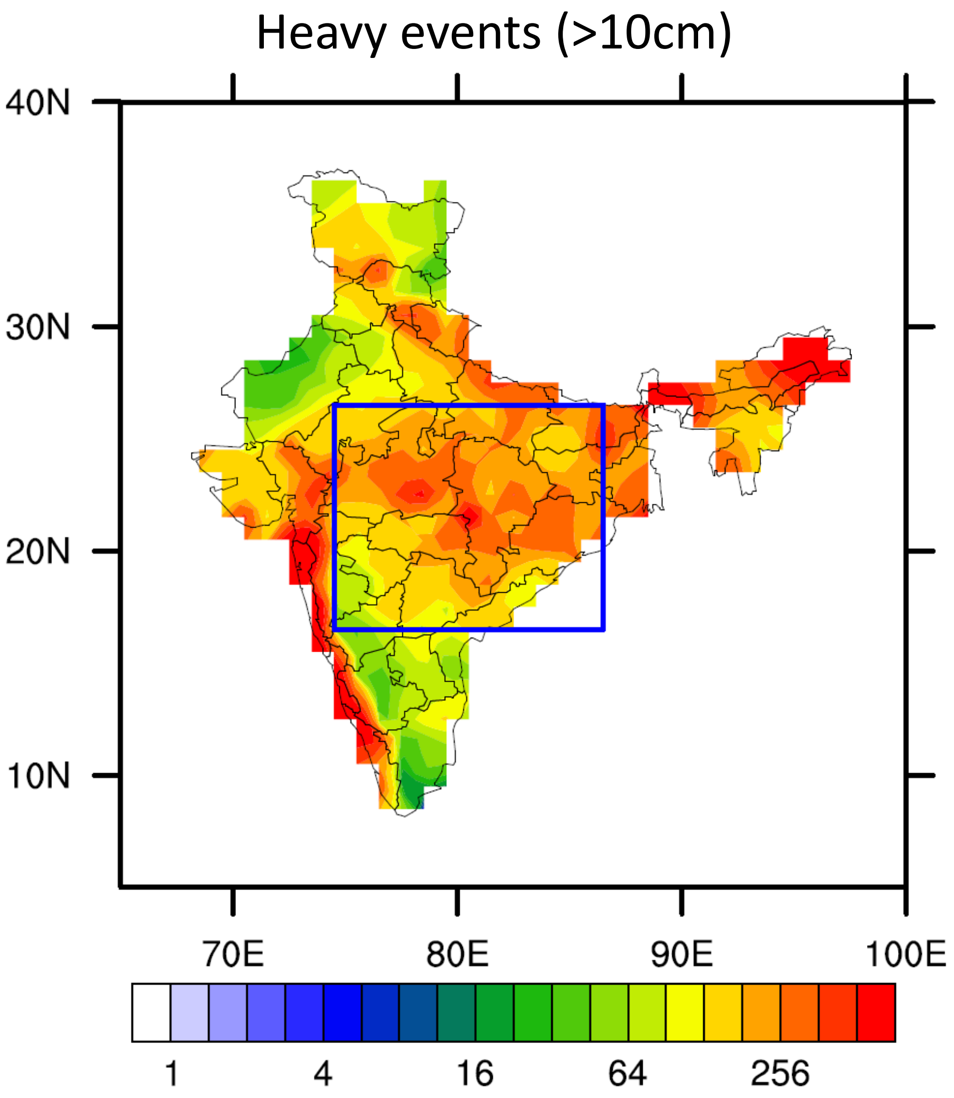
Rainfall category	IMD (mm/ day)
Light	≥0.1 to <7.5
Moderate	≥7.5 to <35.5
Heavy	≥35.5 to <124.4
Extreme	≥124.4

Boyaj, Sinha, Mohanty, Vinoj, Ashok, Sahidul, Kaginalkar, Khare (Atmos Res 2024)

Changes in Extreme rain spells over Central parts of India

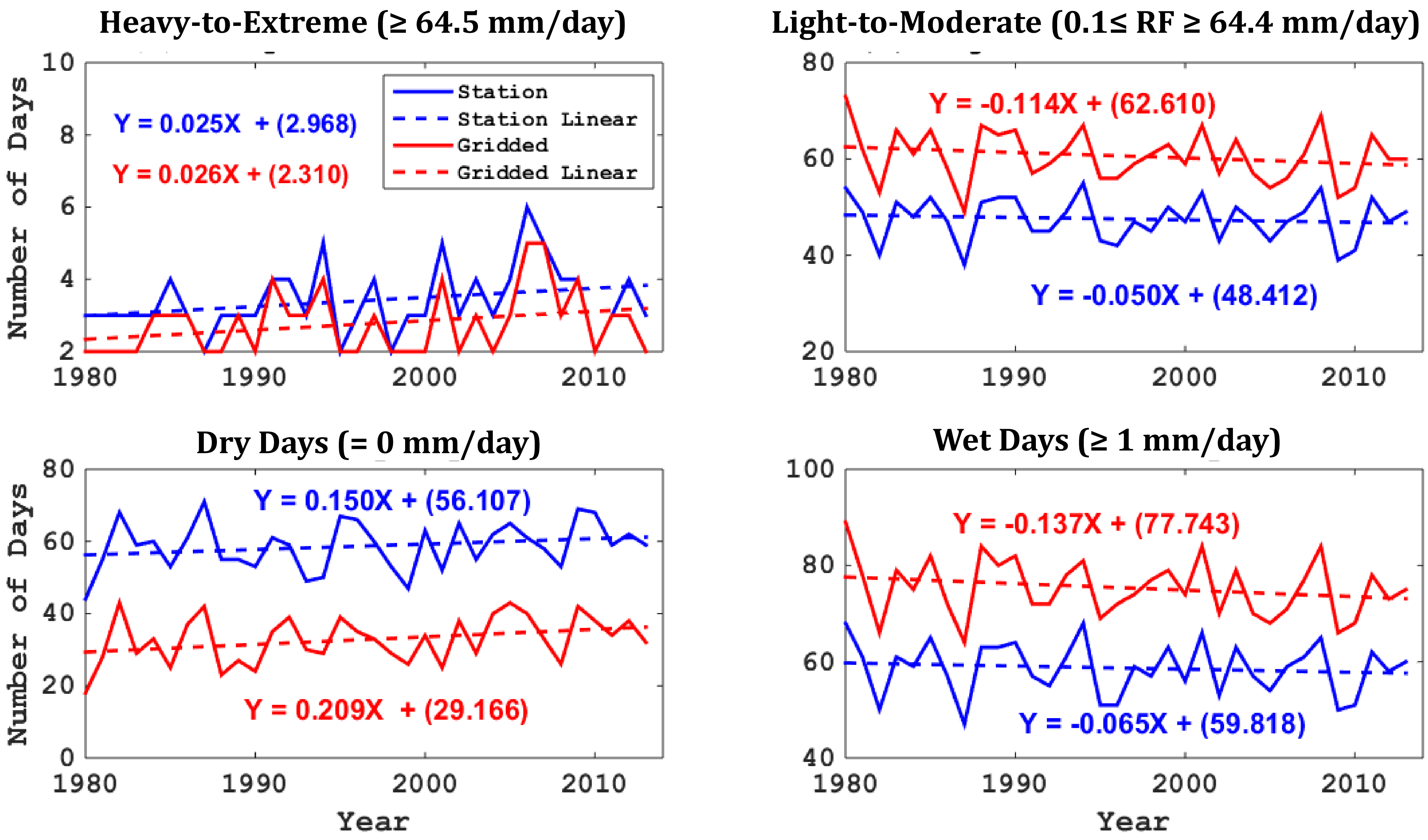


Time series of Extreme rain days count over Central India



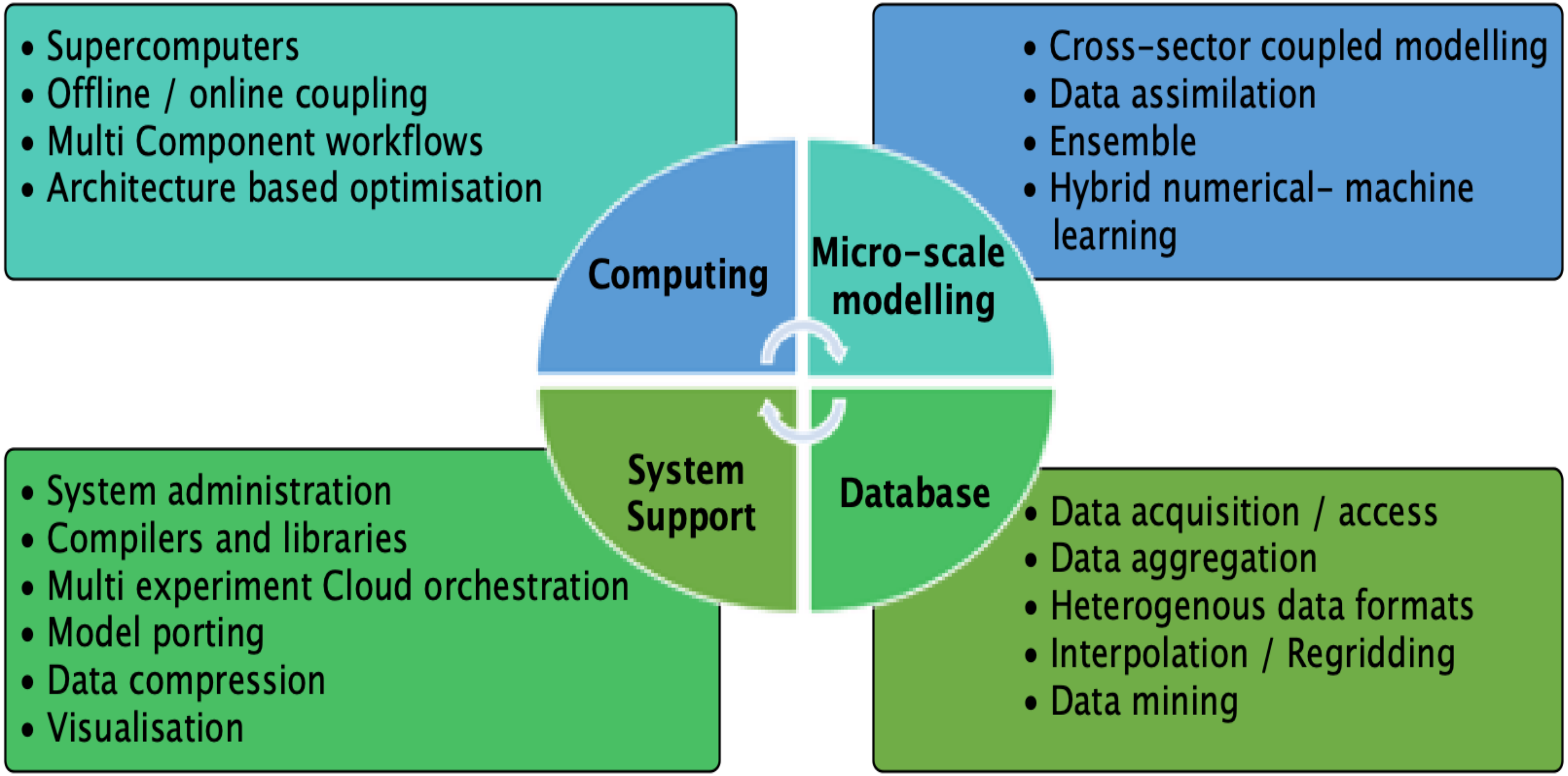
Goswami et al. 2006

Frequency Indices over Odisha for JJAS (1980 – 2013)

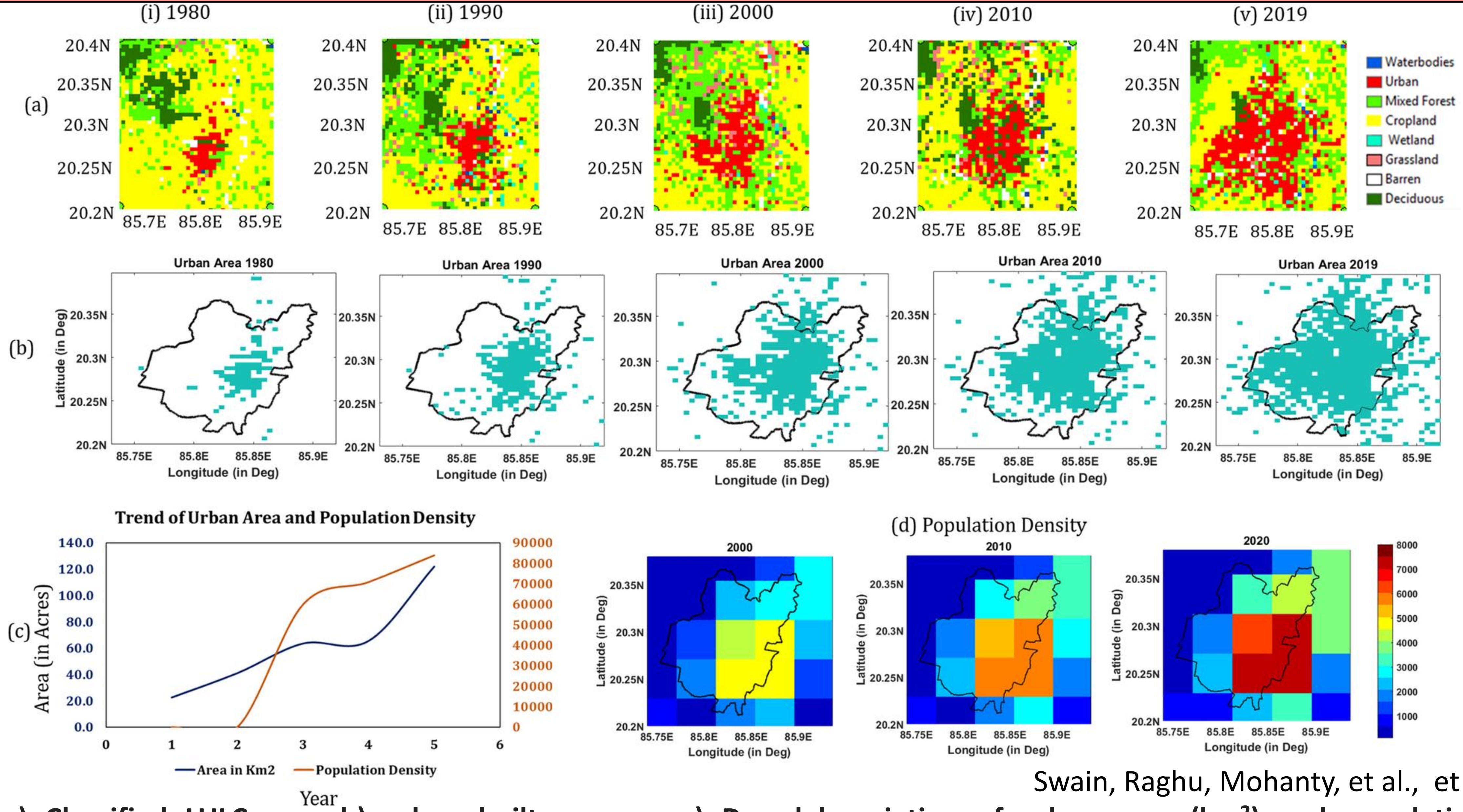


Swain, Sinha, Mohanty, & Pattnaik, 2019

Urban Environment



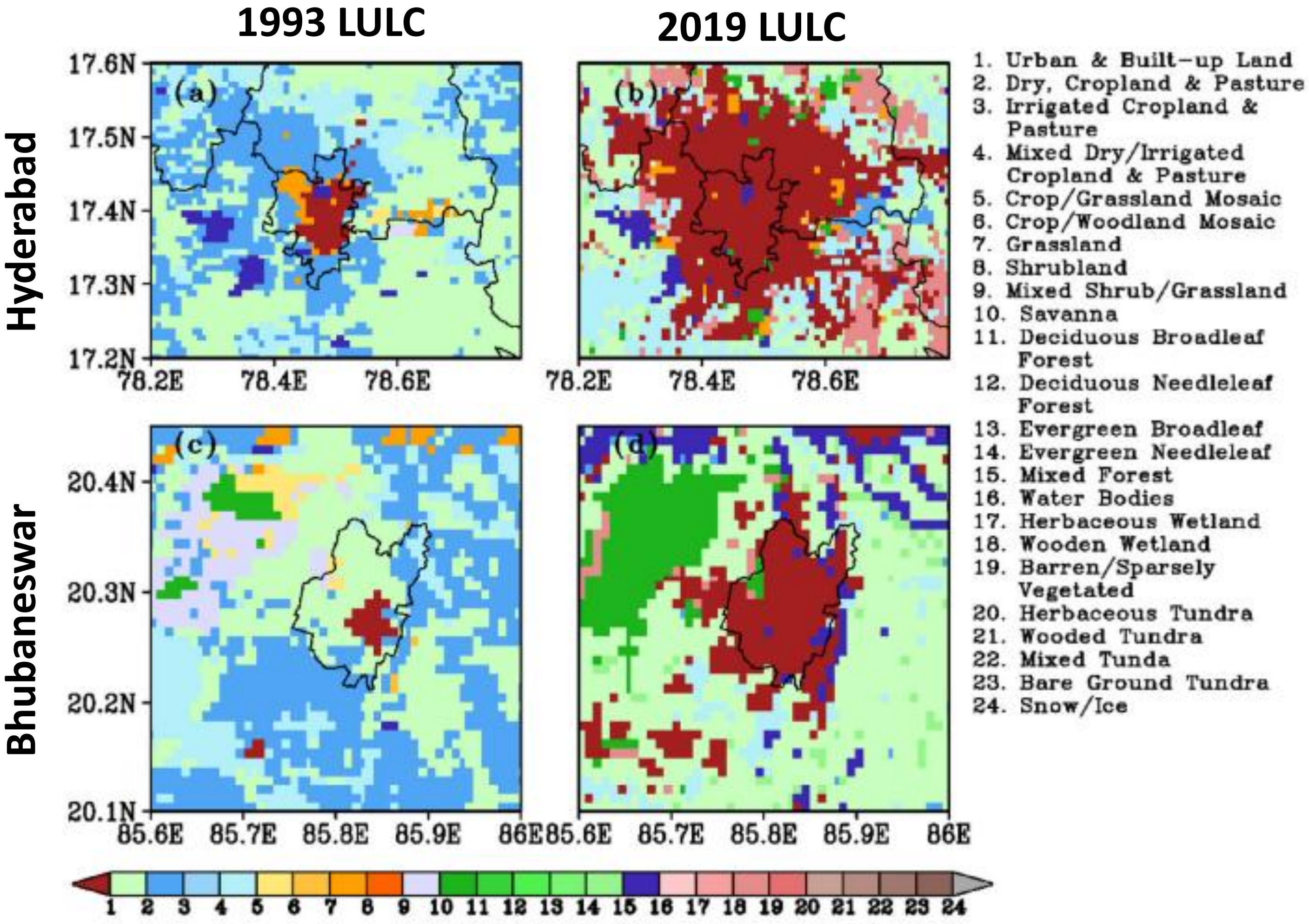
The changes in LULC vs Population density



Swain, Raghu, Mohanty, et al., et al., 2023

a) Classified LULC map b) urban built-up area, c) Decadal variation of urban area (km^2) and population density, and d Spatial distribution of population density over Bhubaneswar for 2000, 2010, and 2020 year

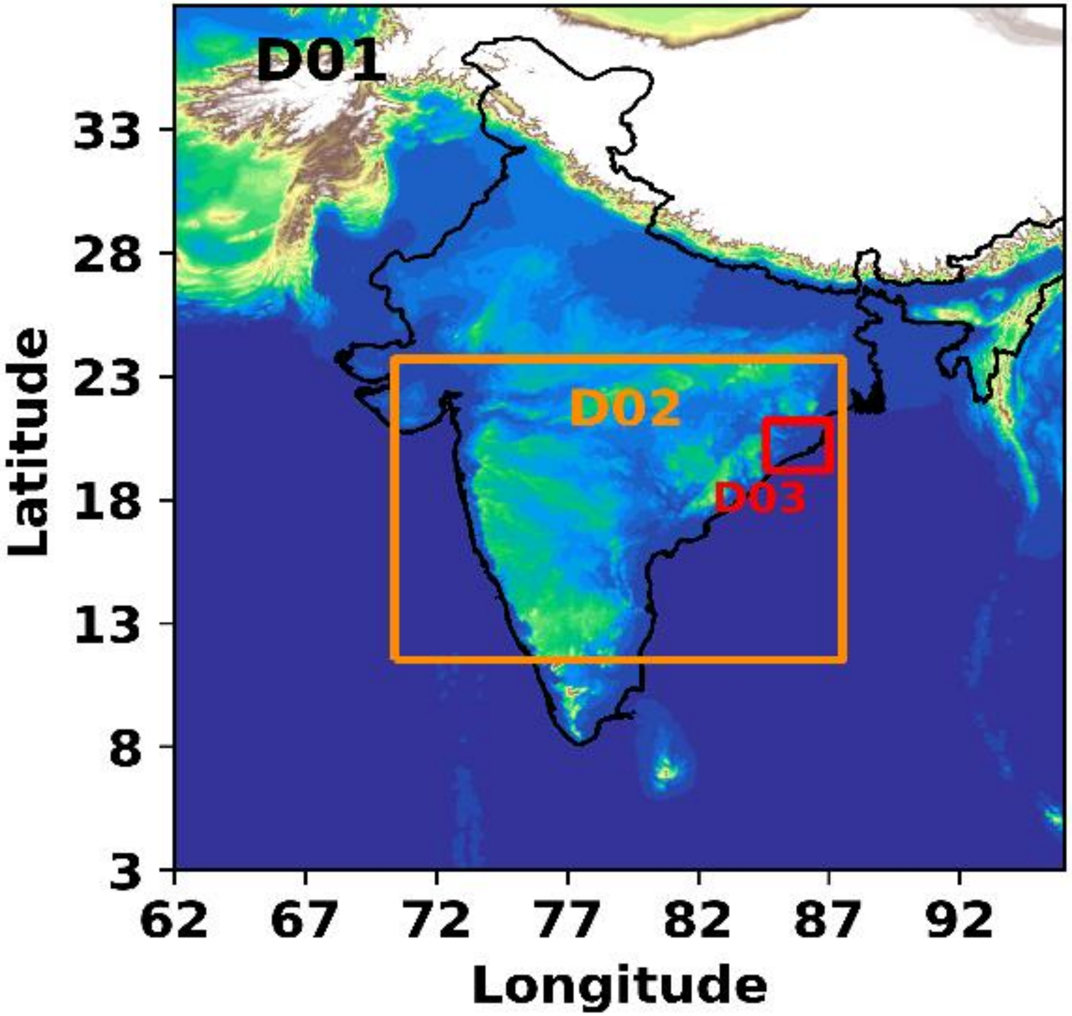
The change of LULC over India Cities: Hyderabad



- ➢ The urban region expanded by 13 and 11 times over a period of 27 years, from 1993 to 2019, in Hyderabad and Bhubaneswar, respectively.

Boyaj, Karrevula, Sinha, Patel, Mohanty, Niyogi, 2024

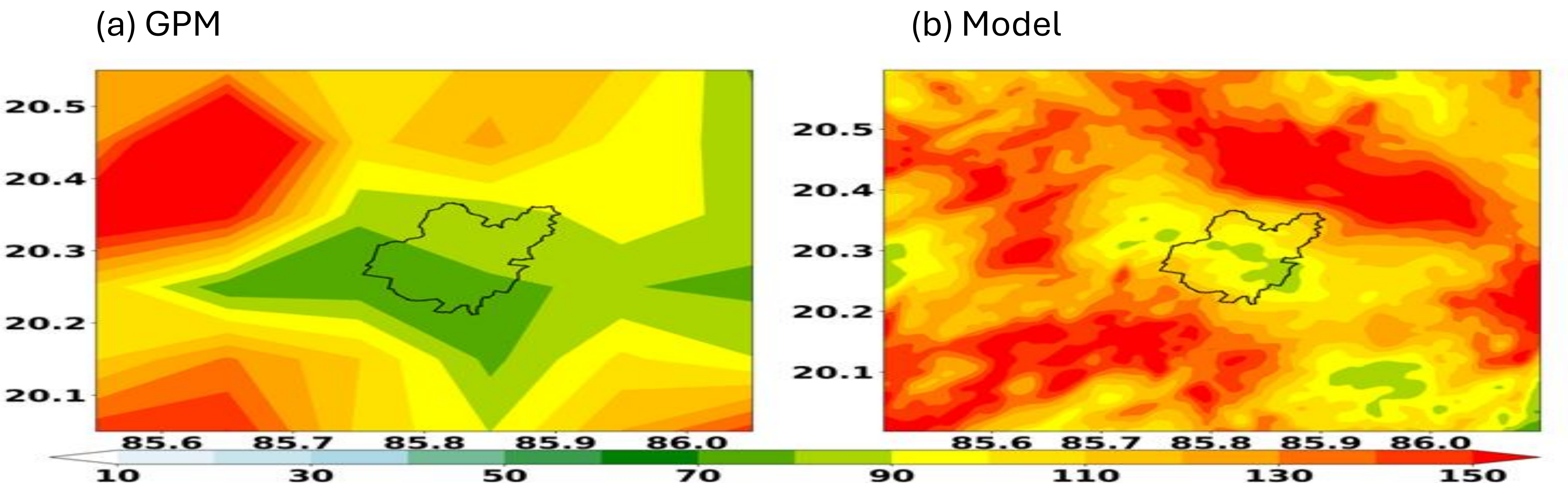
WRF Model domain and Configuration



Parameterization schemes	
LULC	AWiFS (Gharai et al. 2018)
Resolution	4500 x 1500 x 500 m
Microphysics	Ferrier (Ferrier, 1994)
	Lin (Lin et al. 1983)
	Thompson (Thompson et al. 2008)
	WSM6 (Hong & Lim 2006)
Radiation physics	Rapid Radiative Transfer Model (Mlawer et al. 1997) for Longwave Goddard (Chou and Suarez, 1999) for Shortwave
Land-surface physics	Noah (Tewari et al., 2004)
	Noah-MP (Niu et al. 2011, Yang et al. 2011)
Cumulus	Kain-Fritsch (Kain, 2004)
	Betts-Miller-Janjic (Janjić et al. 1994)
	Multi-Scale Kain-Fritsch (Zheng et al. 2016, Glotfelty et al. 2019)
	No cumulus
Planetary boundary layer	Bougeault Lacarrere (Bougeault & Lacarrere, 1989)

Karrevula, Raghu, Sinha, Shyama, Boyaj, Swain,Mohanty, 2024

Performance evaluation of rainfall events using 32 combinations of sensitivity experiments



- Using the WRF model, a series of sensitivity experiments have been carried out by changing the various parameterization schemes to establish an improved model configuration for predicting EREs across the city of Bhubaneswar, Odisha- one of the most vulnerable cities to heavy rainfall in the recent decades.

Karrevula, Raghu, Sinha, Shyama, Boyaj, Swain, Mohanty, 2024

Statistical performance for the best 8 combinations of HRES

	Parameterization schemes			
	Land-surface	Microphysics	Cumulus	Short form
1	Noah-MP (M)	Ferrier (F)	Kain-Fritsch (K)	MFK
2	Noah-MP (M)	Ferrier (F)	No cumulus (N)	MFN
3	Noah-MP (M)	Ferrier (F)	Multi-Scale Kain-Fritsch (S)	MFS
4	Noah-MP (M)	WSM6(W)	Multi-Scale Kain-Fritsch (S)	MWS
5	Noah (N)	Ferrier (F)	No cumulus (N)	NFN
6	Noah (N)	Ferrier (F)	Multi-Scale Kain-Fritsch (S)	NFS
7	Noah (N)	Lin (L)	No cumulus (N)	NLN
8	Noah (N)	WSM6 (W)	No cumulus (N)	NWN

Kling-Gupta Efficiency (Gupta et al., 2009):

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$$

$$\beta = \frac{\mu_m}{\mu_o}, \qquad \gamma = \frac{\sigma_m/\mu_m}{\sigma_o/\mu_o}$$

where, 'r' represents the CC between simulations (m) and observations (o), 'β' stands for the bias ratio, 'γ' denotes the variability ratio, 'μ' signifies the mean observation, and 'σ' represents STD.

Combination	Mean (mm)	Median (mm)	STD (mm)	CC	MAPE (%)	MAE (mm)	RMSE (mm)	KGE
With the station rainfall dataset								
IMD	74.4	66.6	50.5					
MFK	28.6	24.4	22.3	0.38	80.71	51.45	65.47	0.37
MFN	32	26.3	27.5	0.30	103.70	54.08	65.43	0.37
MFS	**46.7**	45.2	**40.5**	-0.01	167.74	60.39	70.72	**0.53**
MWS	**45**	46.1	**36.8**	0.18	140.57	53.95	63.99	**0.55**
NFN	35.9	32.5	28.1	0.27	101.60	52.81	63.63	0.46
NFS	**48.6**	45	**41.7**	-0.11	167.85	66.24	73.53	**0.56**
NLN	**50.4**	43.2	**42.9**	-0.08	145.34	63.28	72.83	**0.59**
NWN	40	37.4	32.7	0.14	120.92	54.50	65.83	0.49

STD = Standard deviation, CC = Correlation coefficient, MAPE = Mean absolute percentage error, MAE = Mean absolute error RMSE = Root mean square error, FB = Fractional bias, IOA = Index of Agreement, KGE = Kling-Gupta Efficiency

Boyaj, Karrevula, Swain, Sinha, Raghu, Sahidul, Vinoj, Khare, Niyogi, & Mohanty, 2025

LULC Impact on HREs using uWRF model

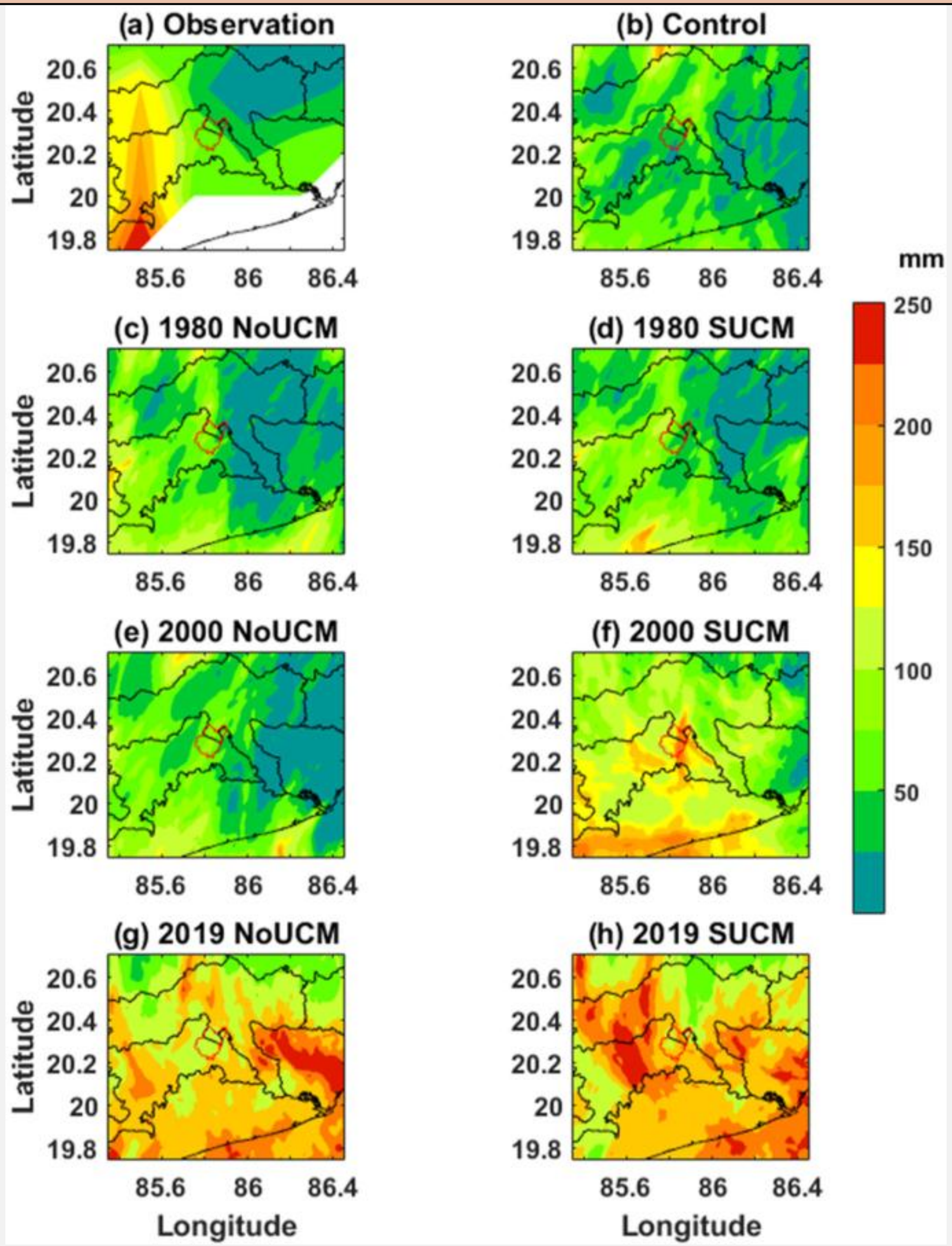


Fig. Accumulated Rainfall on 20 July, 2018

Surface-precipitation feedback (Schär et al., 1999)

$$\triangle P = P' - P = \underbrace{\triangle\chi\,(ET + IN)}_{(I)} + \underbrace{\chi\,(\triangle ET)}_{(II)} + \underbrace{\chi\,\triangle IN}_{(III)} + \underbrace{\triangle\chi\,(\triangle ET + \triangle IN)}_{(IV)}$$

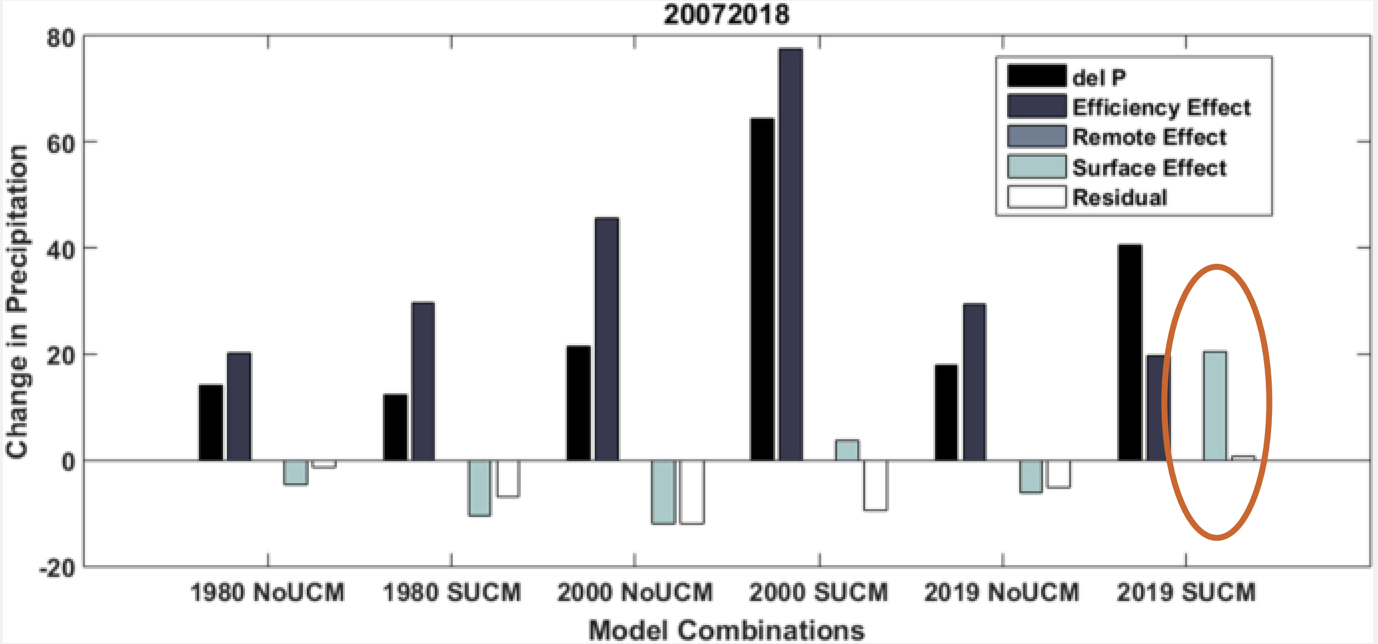
χ = Precipitation efficiency

ET = Evaporation

IN = Moisture influx

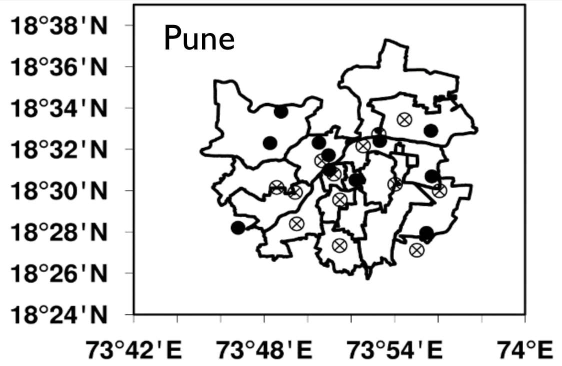
P = Control run

P'= Urban experiments

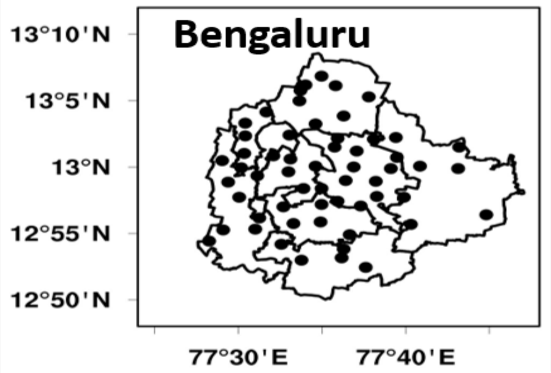


Swain, Raghu, Das, Mohanty & Niyogi, 2024

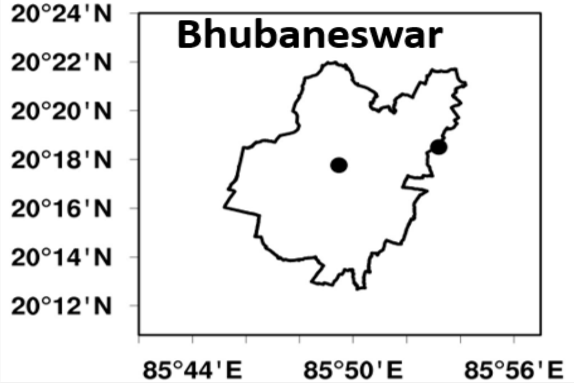
REALTIME PREDICTION OF 2022 MONSOON HEAVY RAINFALL OVER BHUBANESWAR, BANGALORE, AND PUNE



Event Day	Obs Rainfall (mm/day)
12-07-2022	171.5
14-07-2022	69.5
18-08-2022	69
12-09-2022	117.5
15-10-2022	75
18-10-2022	132.5



Event Day	Obs Rainfall
02-08-2022	104.5
03-08-2022	97.5
25-08-2022	65
26-08-2022	76
27-08-2022	66
29-08-2022	109
04-09-2022	148.5
05-09-2022	99



Event Day	Obs Rainfall
05-07-2022	75
16-07-2022	86
02-08-2022	65
14-08-2022	62
12-09-2022	66
22-09-2022	104

Total no. of HRE cases

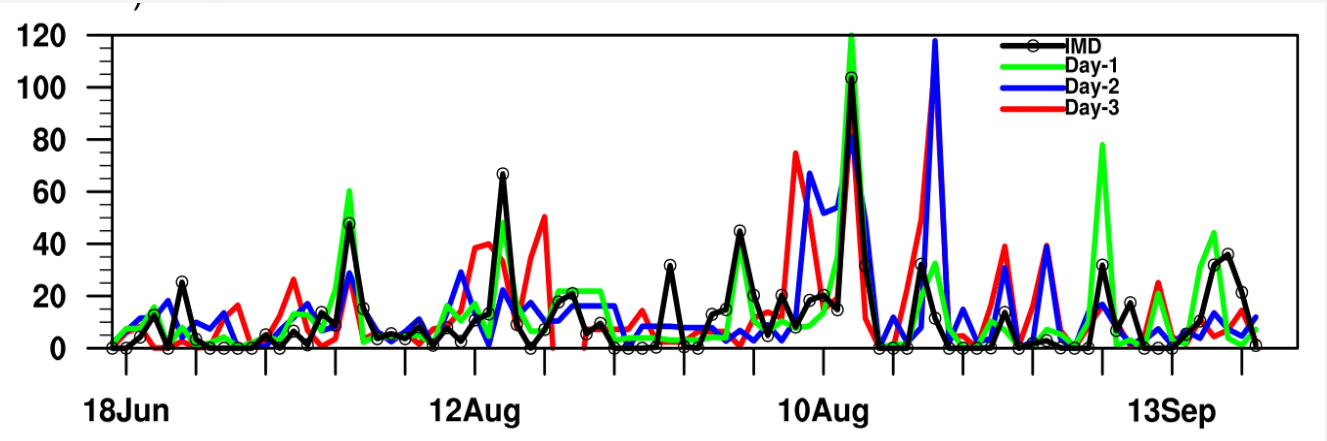
Pune – **6**; Bengaluru – **8**; Bhubaneswar – **6**

Experiments:

- Two-Nested Domain (4.5×1.5)
- Three-Nested Domain (4.5×1.5×0.5)
- 3-day forecast in everyday simulation
- IC/BC: NCEP GFS

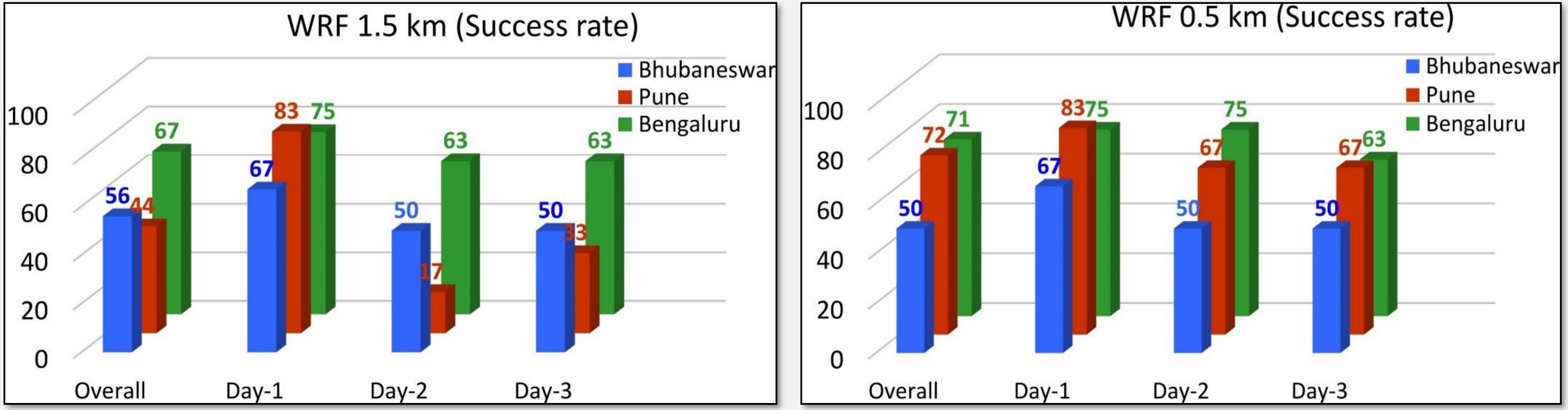
Observation stations:

● ○ IMD AWS/KSNDMC/Smart city/ Mahaved/Skymet



Resolution Impact: 1.5 vs 0.5 km

Model Success Rate in percentage (%)



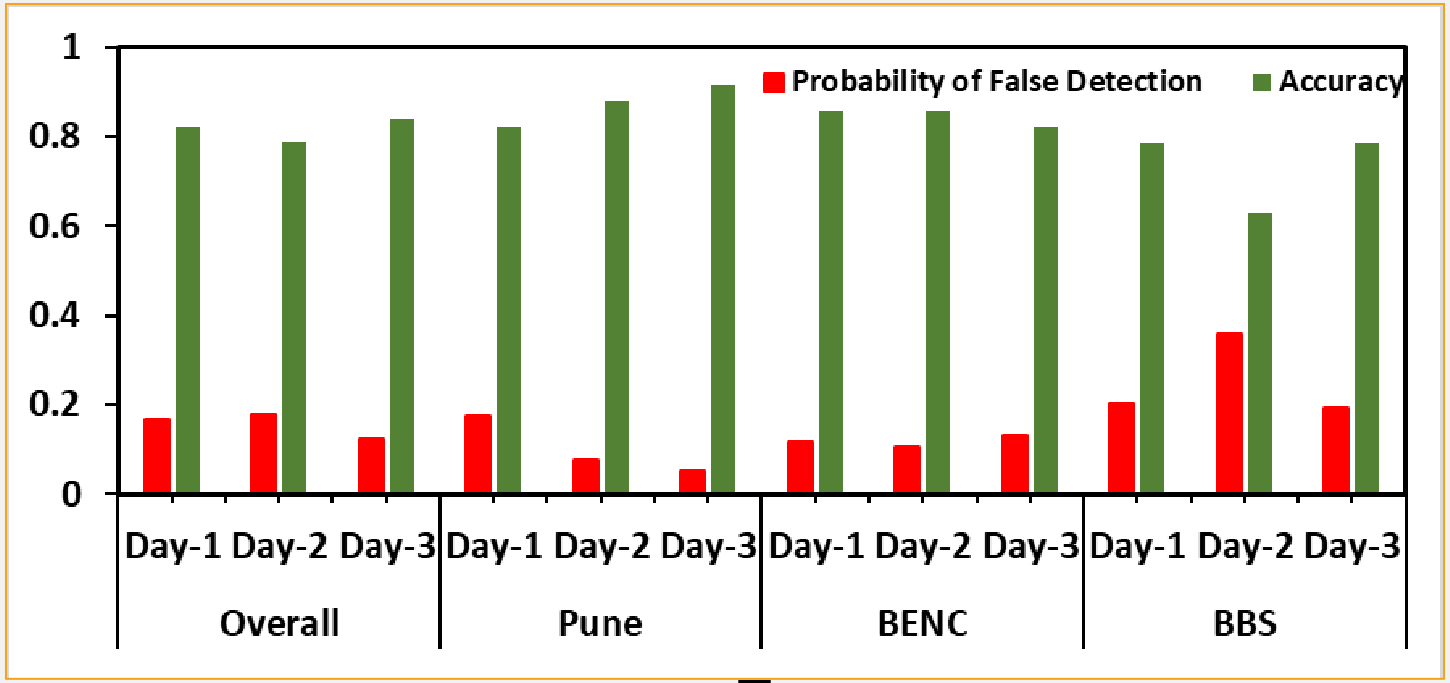
- Significant improvement in the overall "**Success Rates and Forecast Lead Time**" using 0.5 km than to 1.5 km

⇩

Possibly better representation of local scale physical processes leads to improvement in the urban scale simulation

Categorical skill scores over Urban cities of India: Monsoon -2022

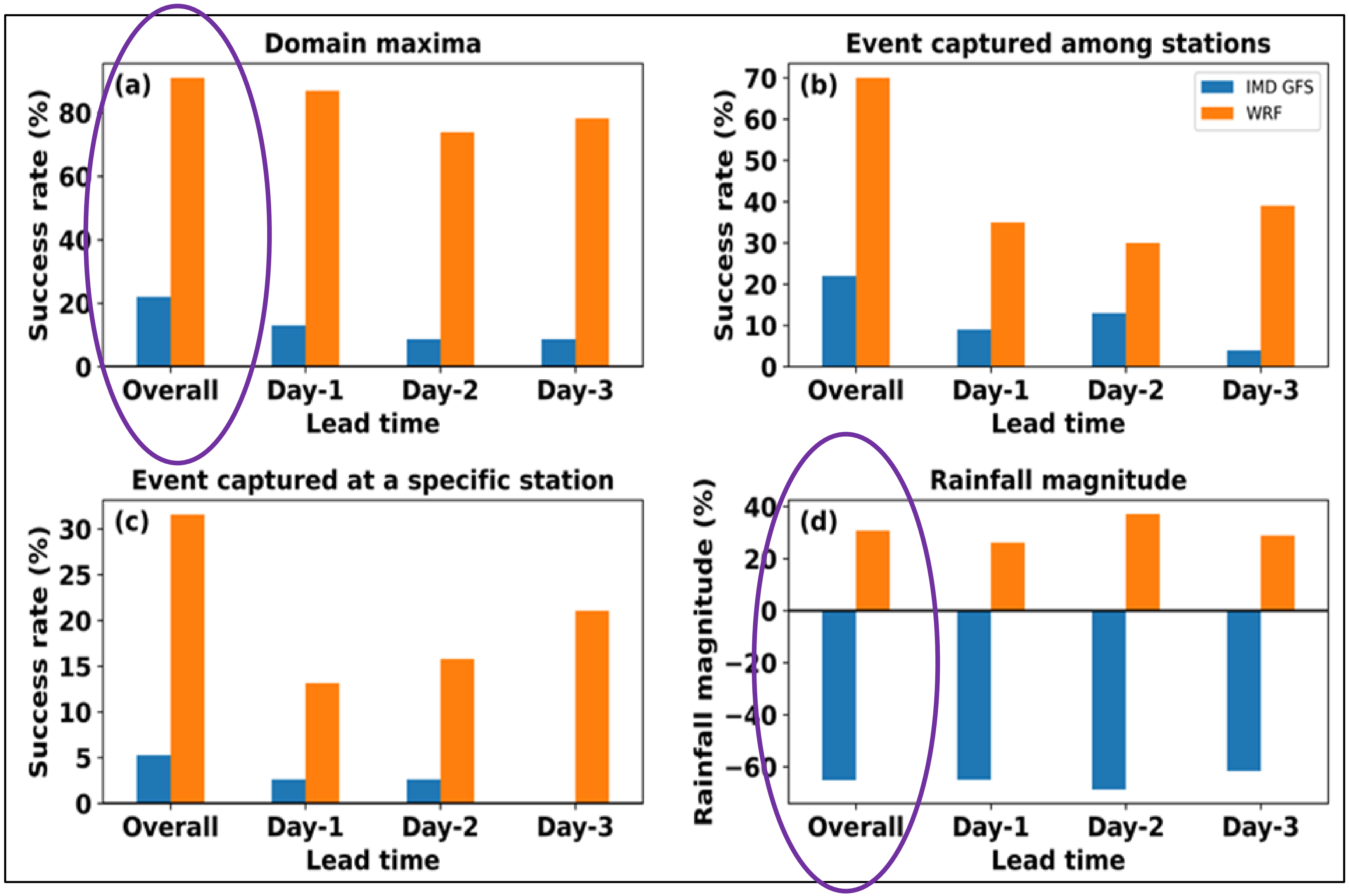
HRE-2022 (combined)	Accuracy	POD	POFD
Day-1	0.821	0.667	0.167
Day-2	0.790	0.389	0.179
Day-3	0.841	0.389	0.124
PUNE	Accuracy	POD	POFD
*Day-1	0.821	0.750	0.175
Day-2	0.881	0.000	0.075
Day-3	0.917	0.250	0.050
BENG	Accuracy	POD	POFD
*Day-1	0.857	0.625	0.118
Day-2	0.857	0.500	0.105
Day-3	0.821	0.375	0.132
BBS	Accuracy	POD	POFD
*Day-1	0.786	0.667	0.205
Day-2	0.631	0.500	0.359
Day-3	0.786	0.500	0.192

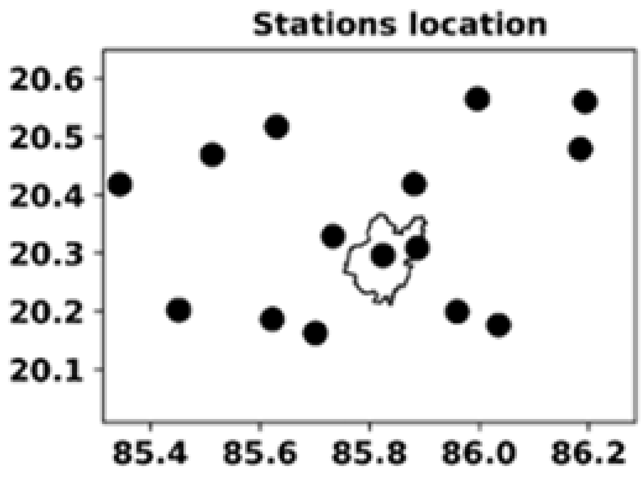


Model - showing better skill in capturing the HRE with less Probability of False Detection (<20%) and more Accuracy (> 63 %)

POD: Probability of detection   POFD: Probability of false detection

Performance of Real-time simulation of uWRF model vs IMD-GFS during 2022





23 HREs compared with uWRF vs GFS using 15 Rain gauge stations in and around Bhubaneswar.

Boyaj, Sinha, Karrevula, Raghu, Vinoj, Sahidul, Khare, & Mohanty, 2025

Success of uWRF simulations vs IMD-GFS

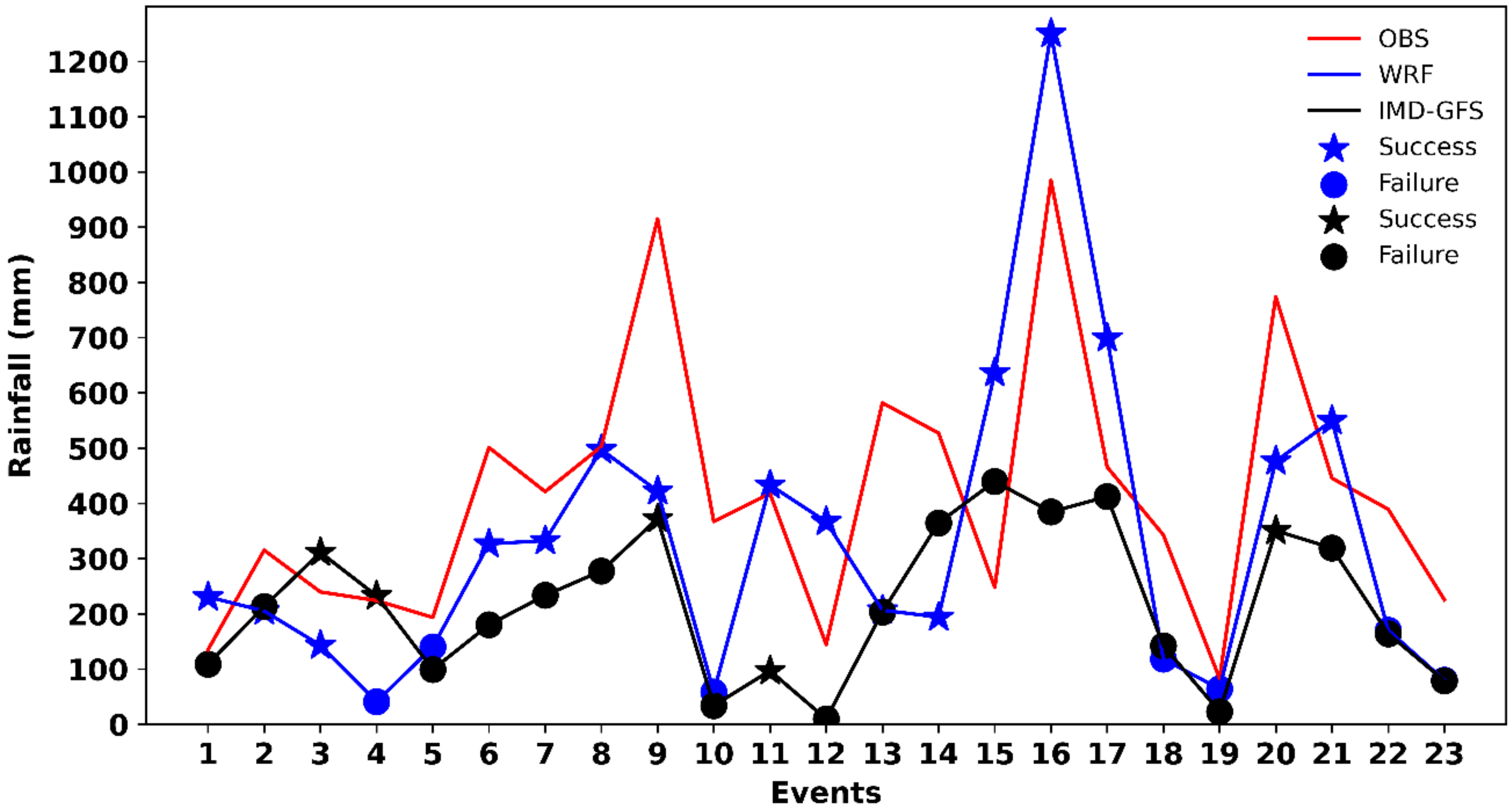


Figure: The line diagram shows the sum of all stations (within the analysis domain) rainfall (mm/day) for each heavy rainfall event.

	Composite Performance	
	WRF	**IMD GFS**
No. success events	26	6
No. failure events	13	33
Total	39	39
Success rate (%)	**67**	**15**
Failure rate (%)	**33**	**85**

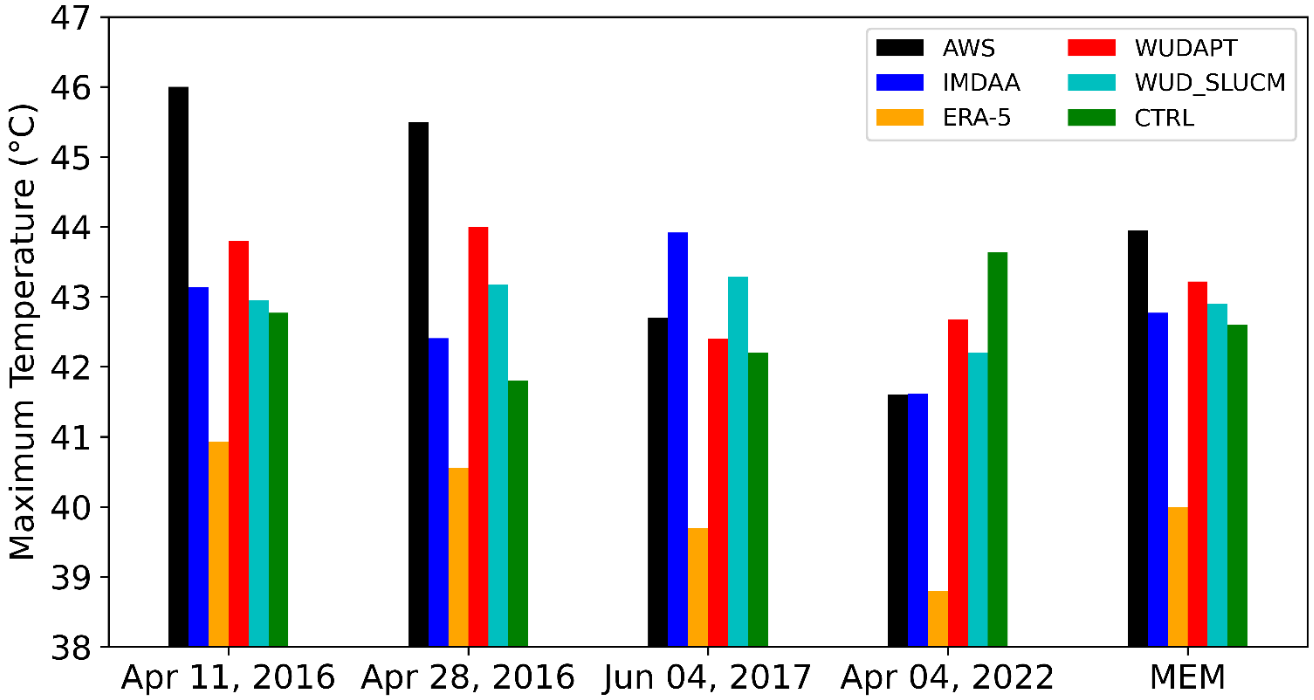
Heavy rainfall (>64.5 mm/day) events in 2022

Bhubaneshwar - 23
Bangalore - 08
Pune - 06

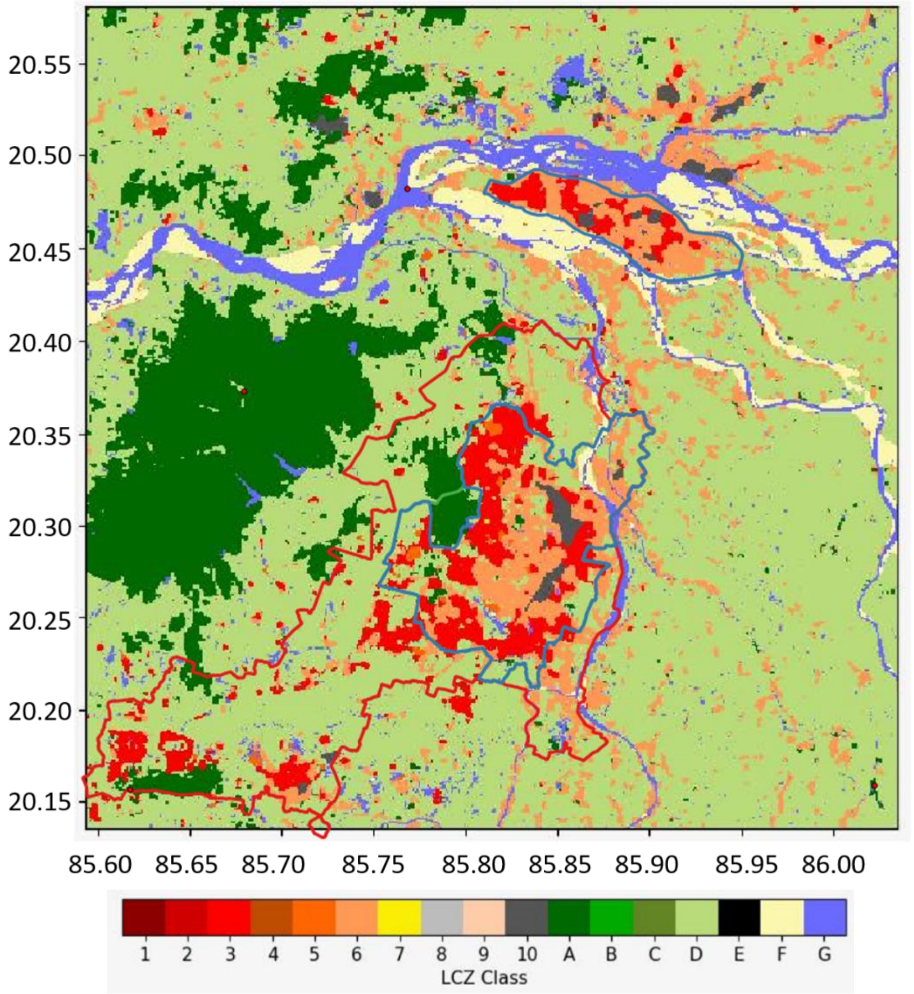
- The False alarm rate for IMD-GFS is 0.78 whereas uWRF is 0.3 over Bhubaneswar city based on 23 HRES and 15 rain Guage stations.

Boyaj, Sinha, Karrevula, Raghu, Vinoj, Sahidul, Khare, & Mohanty, 2025

Impact of Incorporation of WUDAPT-LCZ on heat waves



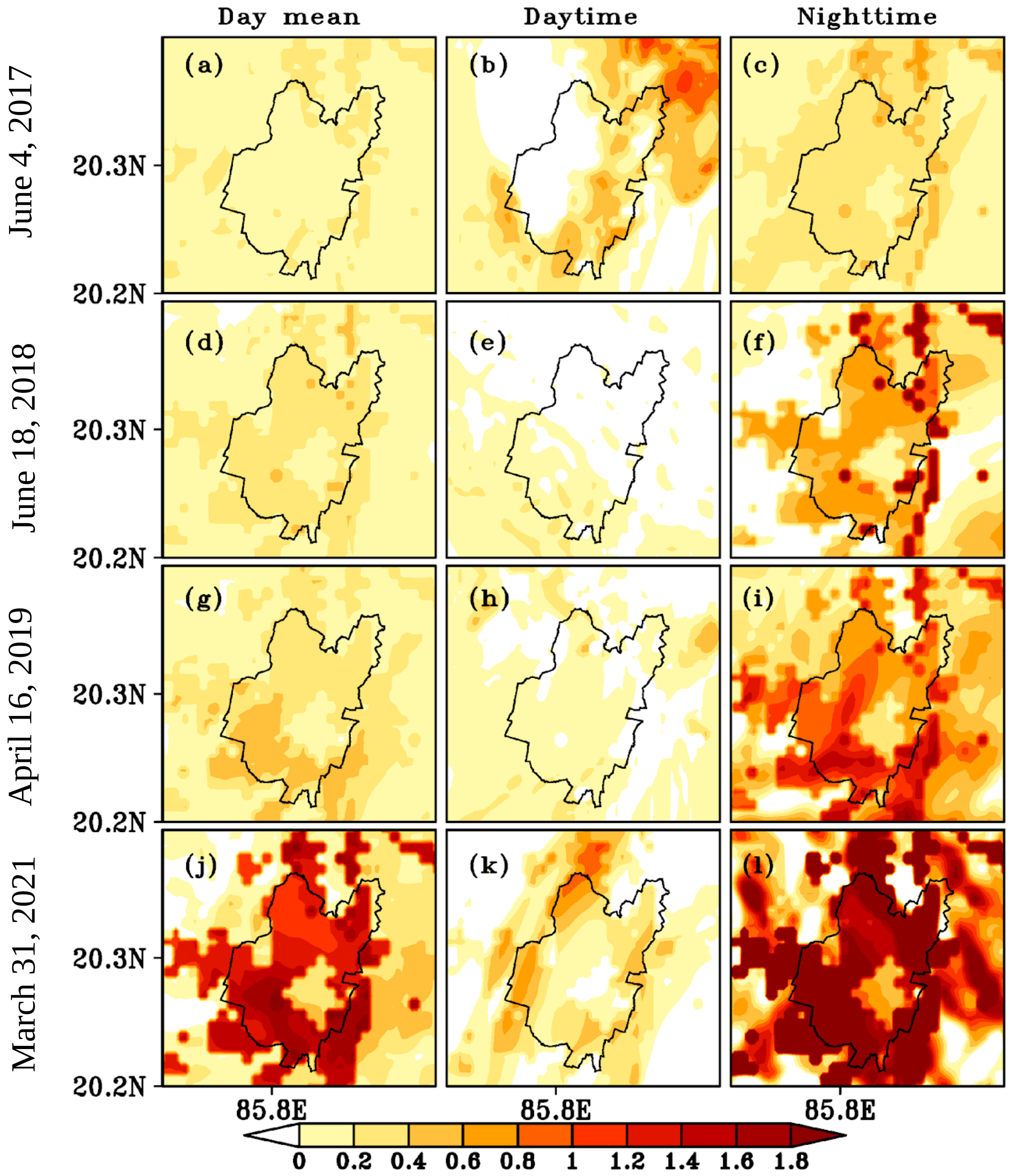
Comparison of Maximum temperature (Model vs Observation)



WUDAPT Local climate Zones

- WUDAPT-driven simulations show approximately a 45% improvement in Tmax compared to the CTRL run when validated against AWS data.

LULC Impact on Heat waves over Bhubaneswar city



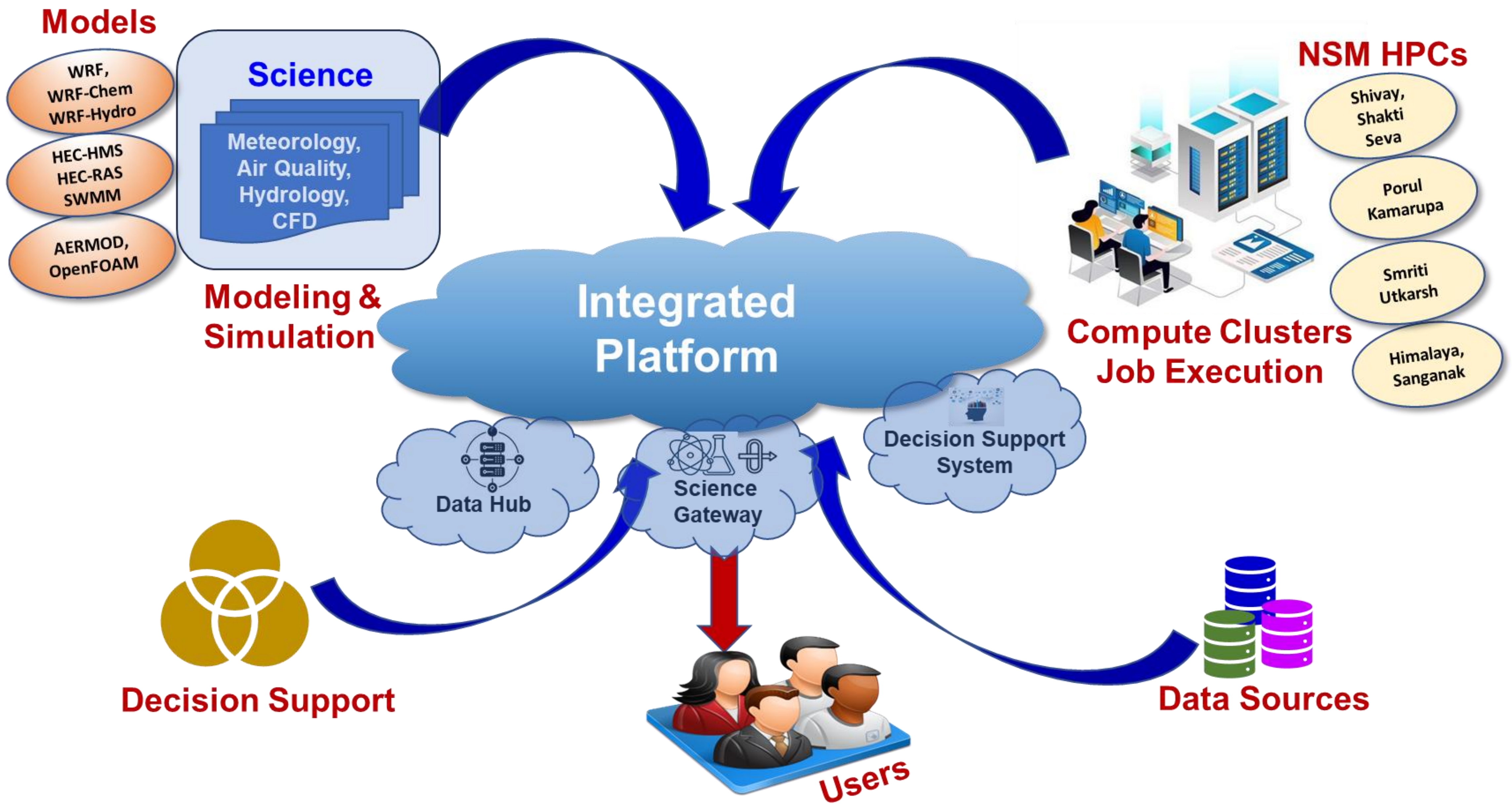
HW events over Bhubaneswar	Daytime UHI (°C)		Nighttime UHI (°C)	
	USGS	ISRO	USGS	ISRO
June 04, 2017	0.28	2.23	-0.12	0.73
June 18, 2018	0.13	0.29	-0.32	3.05
April 16, 2019	1.62	3.02	0.75	2.42
March 31, 2021	-0.02	0.20	1.80	3.80
Average	**0.50**	**1.43**	**0.53**	**2.50**

Urban heat Island (UHI) impact = The difference between the urban and rural temperatures

Figure: Spatial distributions of the discomfort index (°C) from LULC-driven simulations (ISRO-USGS).

Boyaj, Karrevula, Sinha, Patel, Mohanty, Niyogi, 2024

Coupled Urban-Modeling System and DSS



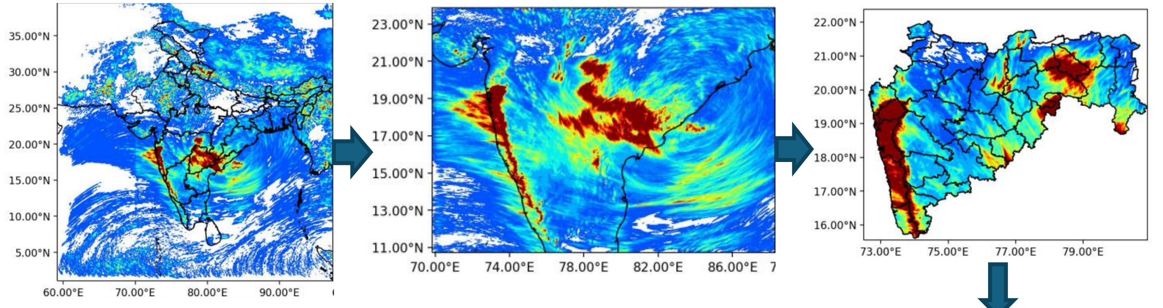
Web based - Integrated System
Science to Society

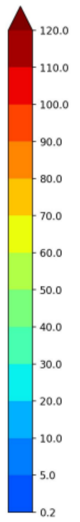
Features

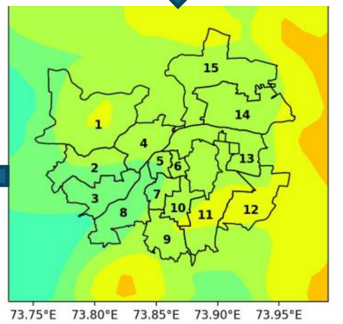
- GUI-based Model Simulation
- Scientists & students can configure
- Administrators can prepare advisory, reports, and share with stakeholders
- Operational agency may get facility an end-to-end DSS

Integrated platform for

- Data Accusation
- Automated HPC based Modeling and Simulation
- Postprocessing
- Model Verification
- Observed Data Analysis
- Visualization of the model products
- Decision Support System (DSS)







Example DSS:
Ward-wise/ Area-specific data

Daily rainfall forecast for Pune city (mm/day)
*(*Experimental prediction based on WRF model simulations of NSM-Urban Program)*

	26/07/2023	27/07/2023	28/07/2023
Yeravada-Kalas-Dhanori	26.13	53.40	0.77
Dhole Patil	24.35	52.93	1.27
Nagar Road-Wadgaonsheri	25.09	51.57	0.63
Shivajinagar-Ghole Road	21.05	53.24	1.36
Aundh-Baner	25.03	60.56	0.94
Kothrud-Bawdhan	15.12	46.84	2.90
Warje-Karvenagar	14.44	46.40	2.42

Summary Conclusions

- Understanding and Prediction of Heavy rainfall events during summer monsoon are very important in the context of rapidly growing Urbanization and population over Indian cities.

- More than 500 sensitivity experiments have been carried out to customize the urban WRF model configuration with 500m resolution over Various urban cities of India.

- A spatial shift in rainfall patterns was observed, and the uWRF model tends to overestimate rainfall magnitude by approximately 30%, whereas the IMD-GFS underestimates it by 65% compared to station observations over Bhubaneswar city.

Continue…

- The uWRF setup, The Day 1 and Day 2 forecasts outperform Day 3, highlighting the model's decreasing accuracy with lead time.
- Additionally, the 0.5 km resolution uWRF setup exhibits 10–20% greater skill than the 1.5 km configuration, emphasizing the benefits of higher resolution in accurately simulating urban rainfall extremes.
- The city-scale prediction skill of uWRF (1.5 km & 0.5 km) is significantly higher than the driving GFS IC/BC, demonstrating its enhanced capability in urban-scale forecasting.
- The model remains stable and provides a reliable indication of the occurrence and non-occurrence of HREs, with a success rate exceeding 60% and a false alarm rate below 20%, reinforcing its effectiveness for prediction.

Future Directions

- Mesoscale data assimilation at 1.5/0.5km with the use of Satellite radiance, DWR reflectivity and AWS data expect to further improve the performance of HREs with uWRF model (Mission Mausam).

- Impact of Incorporation of GLOBUS/WUDAPT in uWRF simulation of Monsoonal Rainfall Events over Indian cities.

- Exploring Physics-Aware AI models for Simulating Monsoonal Extreme Rainfall Events with emphasis to growing Urbanization

Open for Questions & Suggestions

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Tropical Cyclones and Associated Storm Surges Prediction

Monsoon Studies: Use of MONEX & FGGE Data on Mechanism of Onset, Progress and Withdrawal Phases

Medium Range Weather Prediction [NCMRWF]

Monthly to Seasonal Scale Prediction of Rainfall and Temperature for Climate Risk Management in Agriculture

Urban Scale Prediction of Extreme Rainfall and Heat Stress[Heat Waves]

Climate Smart Farming

Science for Common People Society [SCOPES]