HPC-enabled Urban Integrated Modeling: Challenges and Solutions

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Centre for Development of Advanced Computing (C-DAC) Pune

National Symposium on

Understanding the science of heatwaves under the warming scenario and challenges ahead

19 March 2024
IITM Pune

Outline

- Background
- Challenges and objectives
- Consortia Programs
- Methodology/Approach
- Integrated/Coupled modeling
- Work done
- Conclusion

Background

- Global urban population projected to be double by 2050
- Rapid urbanization - the driver of economic growth but has environmental challenges
- Need to understand, simulate, and disseminate information about extreme events, city operations, and planning decisions

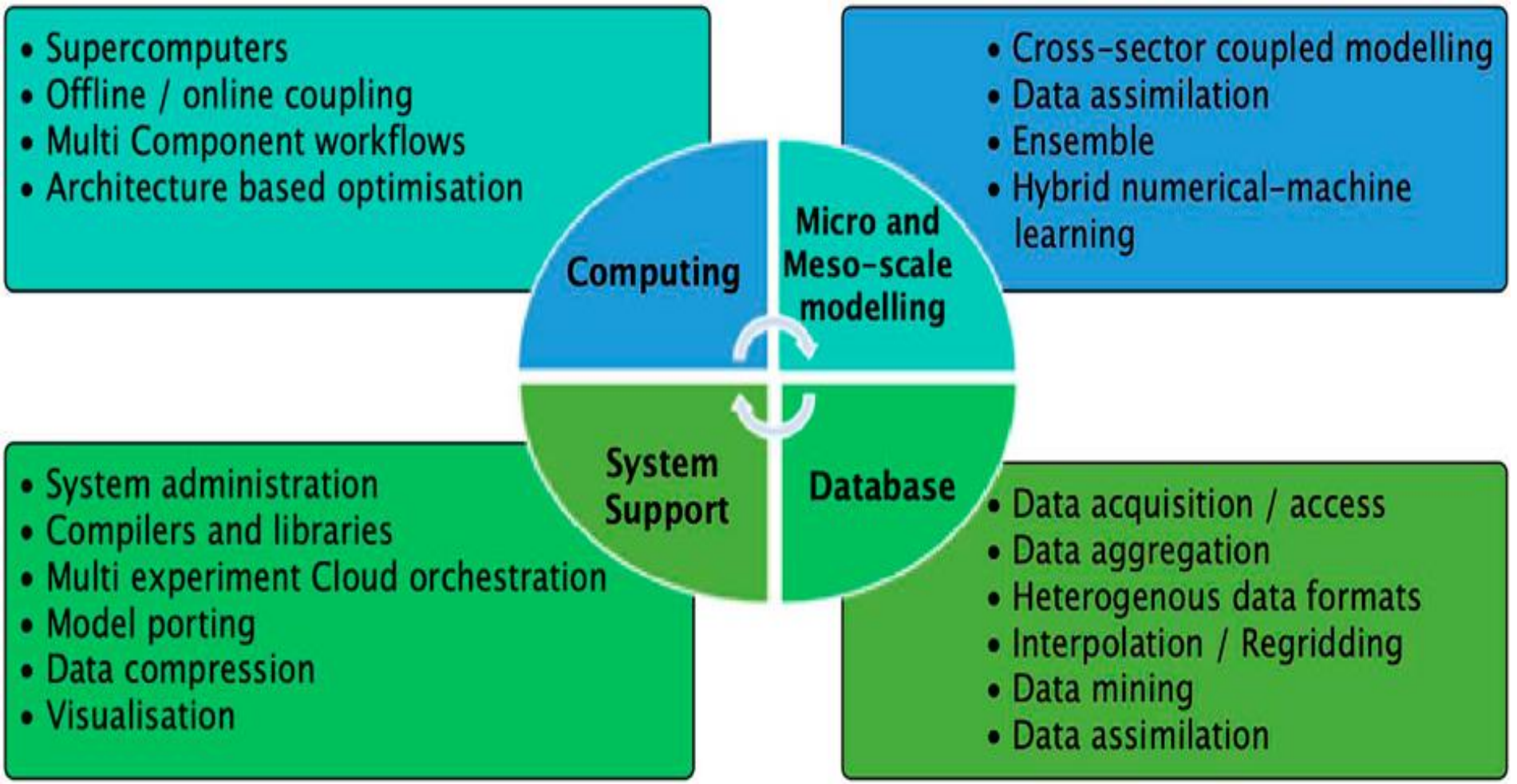
Gaps

- Individual data/information are available with various agencies, but it needs to be curated for specific services
- Urban environment is a co-dependent system requiring **inter-operable** data, products, scientific methods, decisions and impact information at one place
- Citizen centric urban environment services using scientific data
- Multi stake-holder, multi-sector access to a common platform for any city
- City data access for research / end user usage
- Uniform standard operating procedures for data, modeling and DSS applicable to all cities – avoiding duplication of city ICT efforts/cost

Science

NSM **DSS**
Information dissemination
GIS

Integrated modeling and service challenges



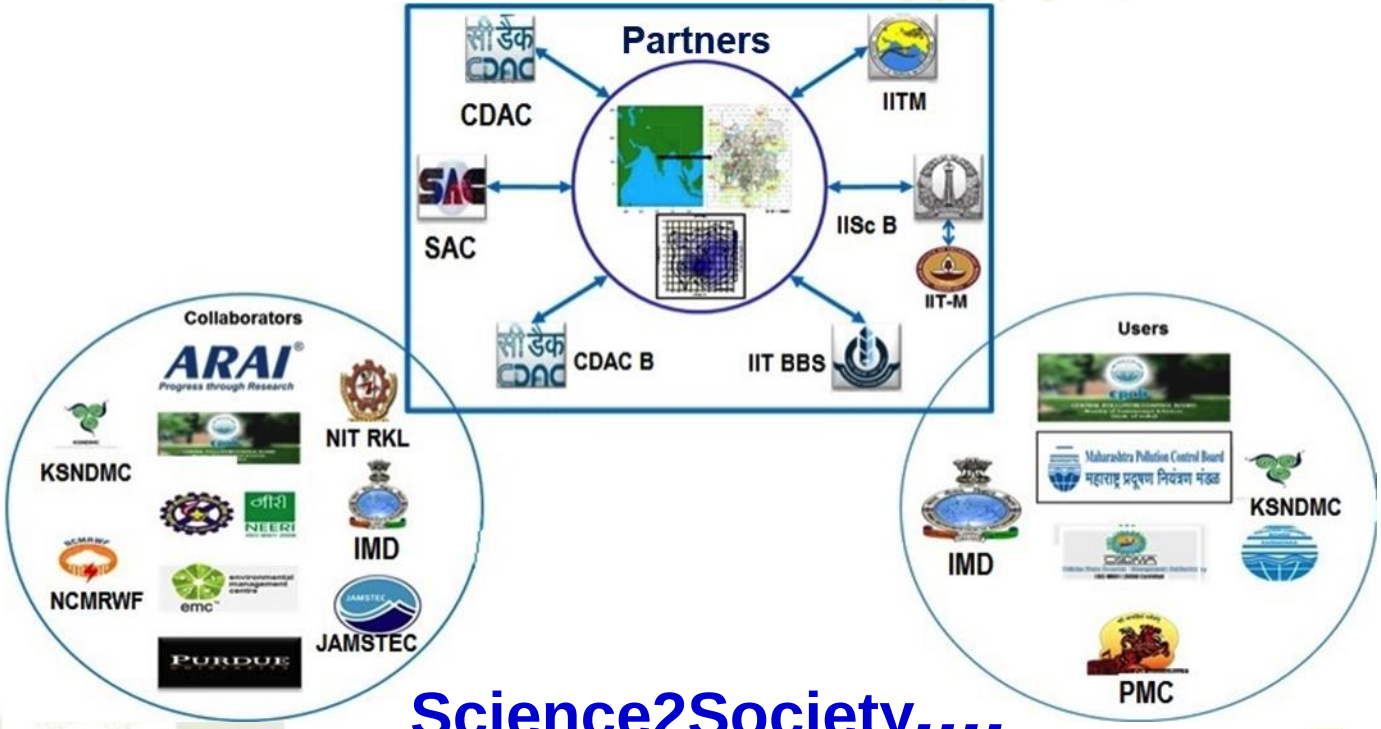
Kaginalkar et al., 2022, BAMS, 103

Objectives

- An effort to frame an interdisciplinary community of meteorology, hydrology, air quality, and computer science (e.g., WMO, 2019)
- Form a consortia program, under the aegis of India's National Supercomputing Mission (**NSM**) to develop an ecosystem "Urban Environment Science to Society" (UES2S) - a science gateway for community research and end-user service
- Study and prediction of urban events involve multiscale observations and cross-sector models, heterogeneous data management, and enormous computing power
- Design HPC-based science cloud platform for urban environment and data science, stakeholder applications, and decision-making
- Facilitate urban researchers with modeling and technology platforms for tailored end-user services

Partnership Formation – Framework Development

Urban Modeling

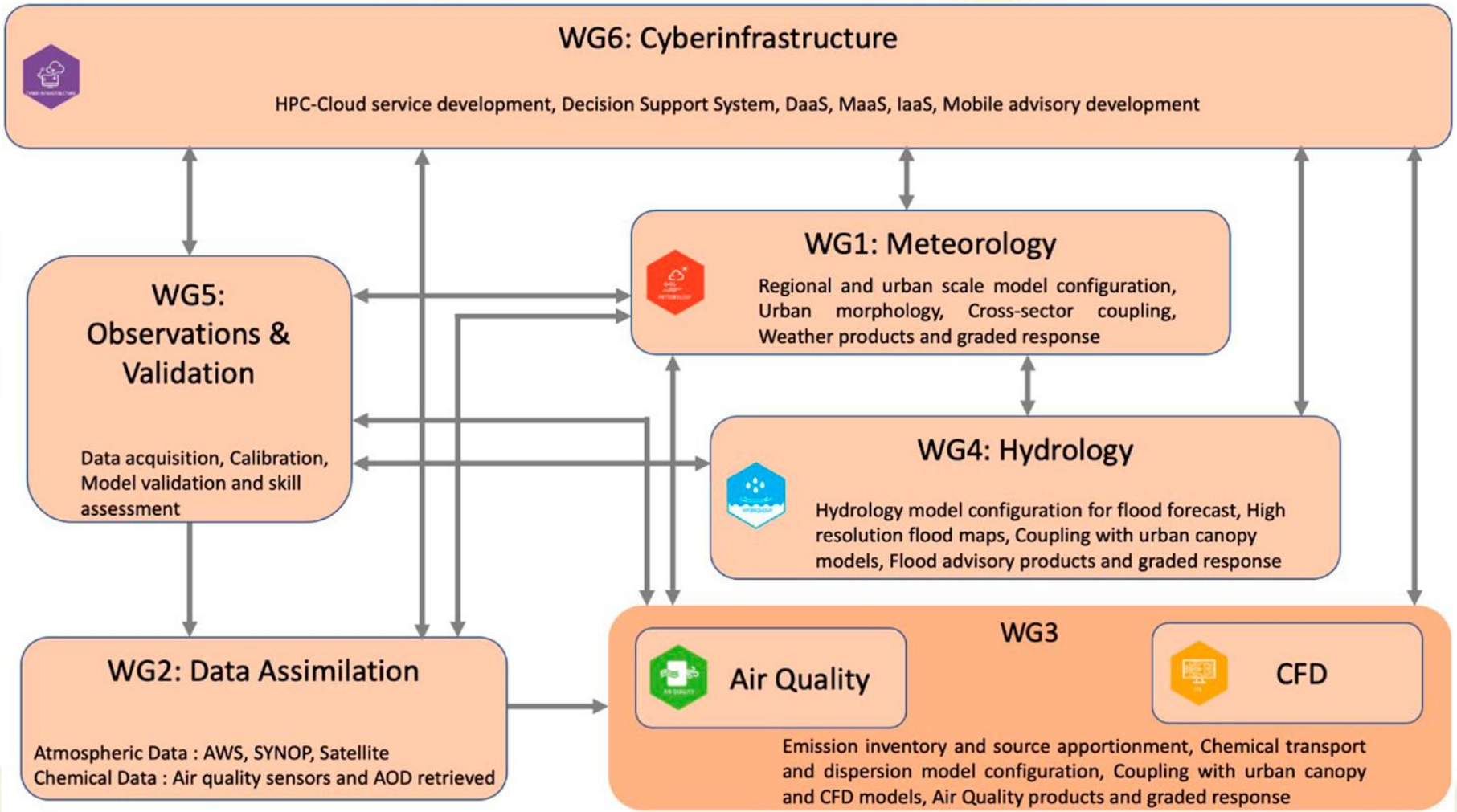


Science2Society….

A framework promoting sustainable goals and resilient Indian smart cities through science and ICT

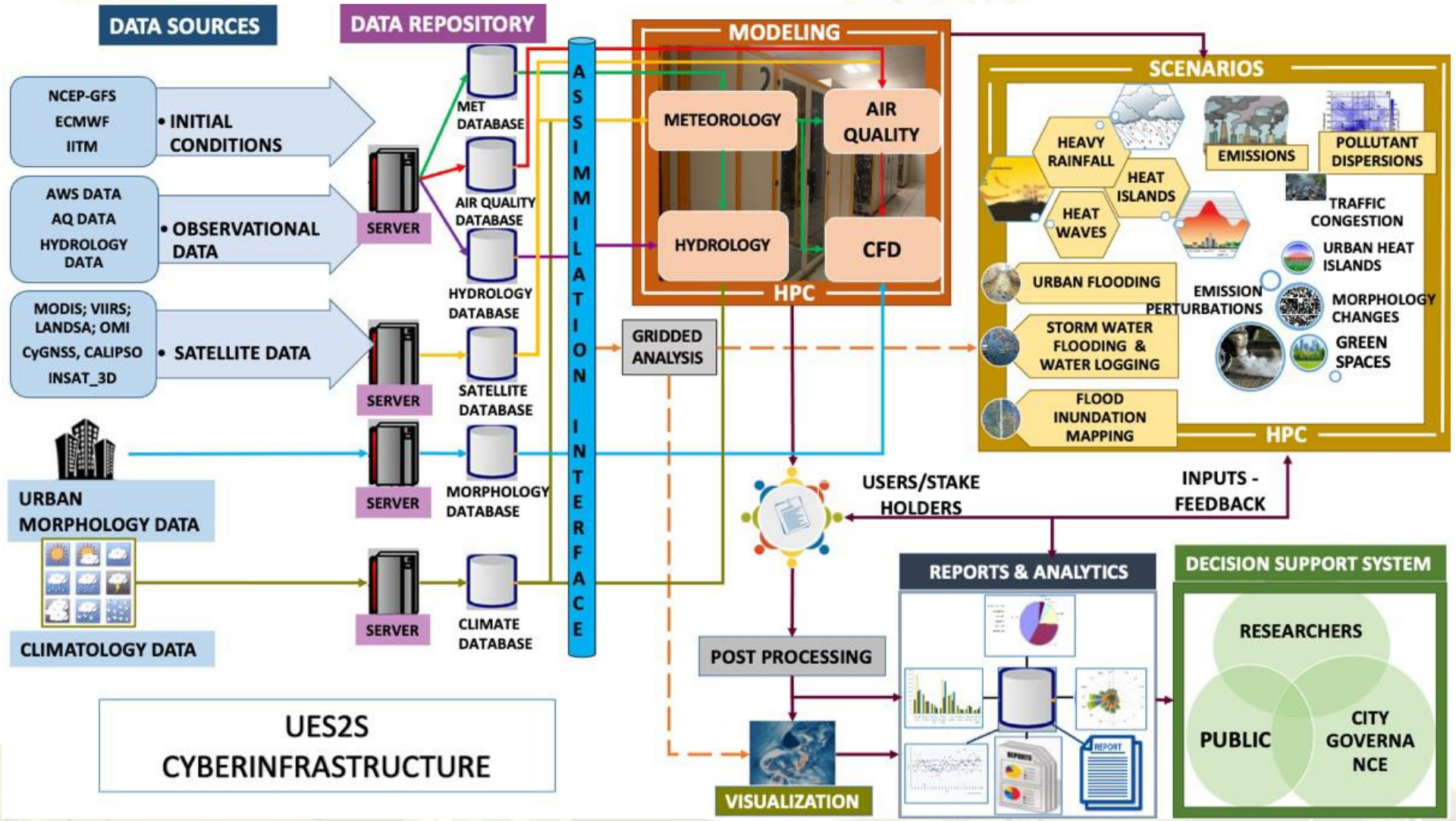
Partnership - Research and Technology Work

urban-scale environment model forecasts and technology groups

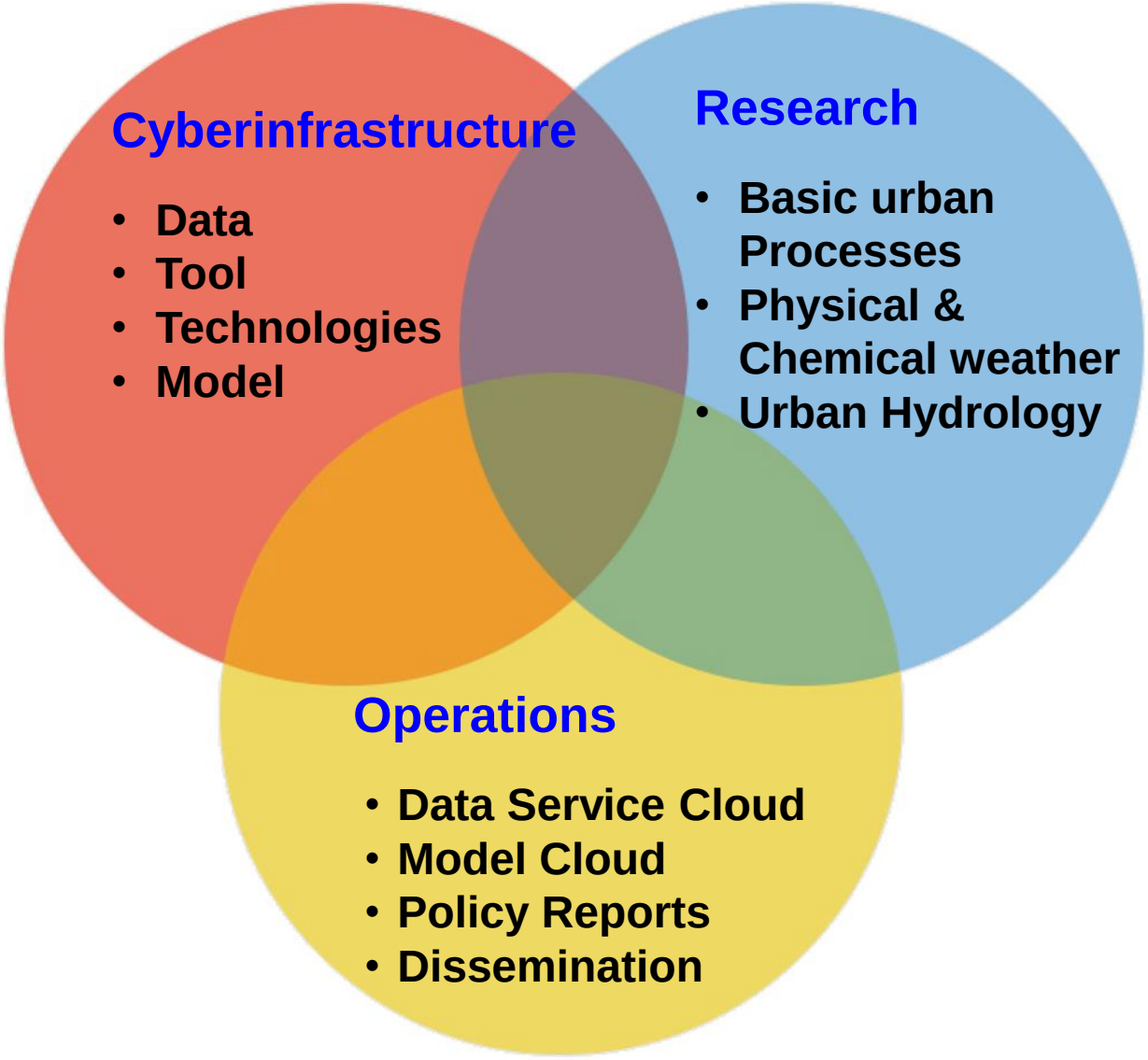


Kaginalkar et al., 2022, BAMS, 103

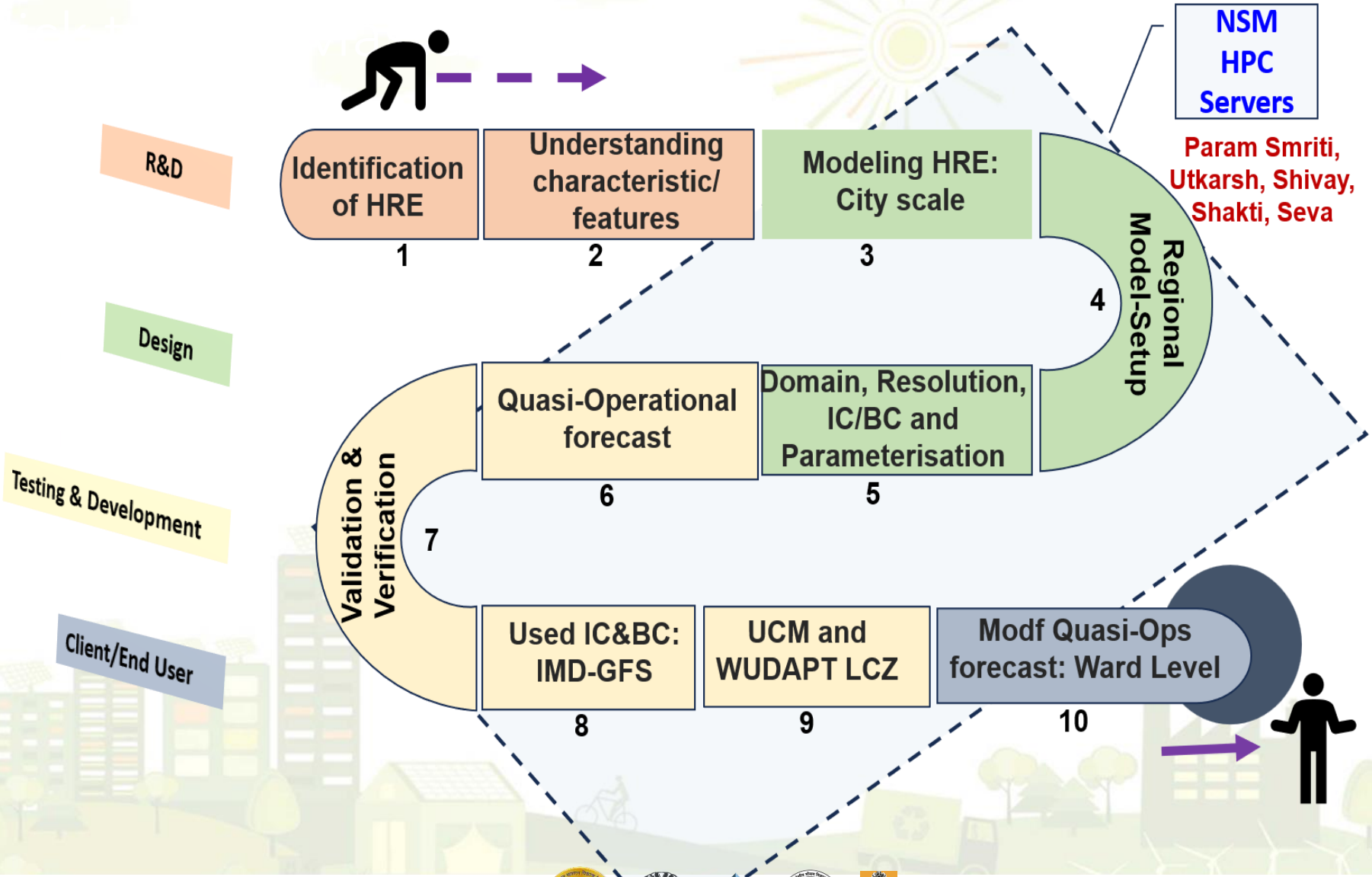
System Overview



Philosophy
Integrated Urban Modeling

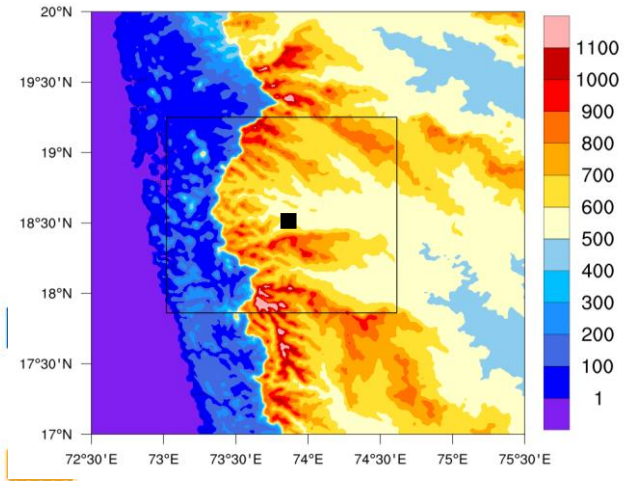


Approach

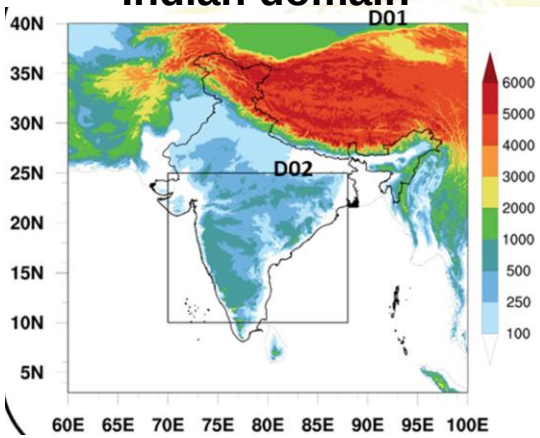

R&D
Design
Testing & Development
Client/End User
Identification of HRE
1
Understanding characteristic/ features
2
Modeling HRE: City scale
3
Regional Model-Setup
4
Domain, Resolution, IC/BC and Parameterisation
5
Quasi-Operational forecast
6
Validation & Verification
7
Used IC&BC: IMD-GFS
8
UCM and WUDAPT LCZ
9
Modf Quasi-Ops forecast: Ward Level
10
NSM HPC Servers
Param Smriti, Utkarsh, Shivay, Shakti, Seva

Domain Sensitivity Experiments

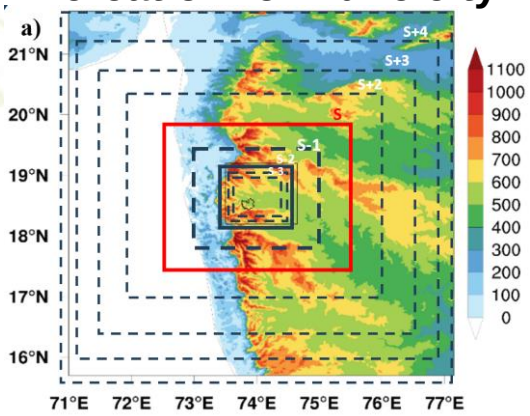
Pune Topography



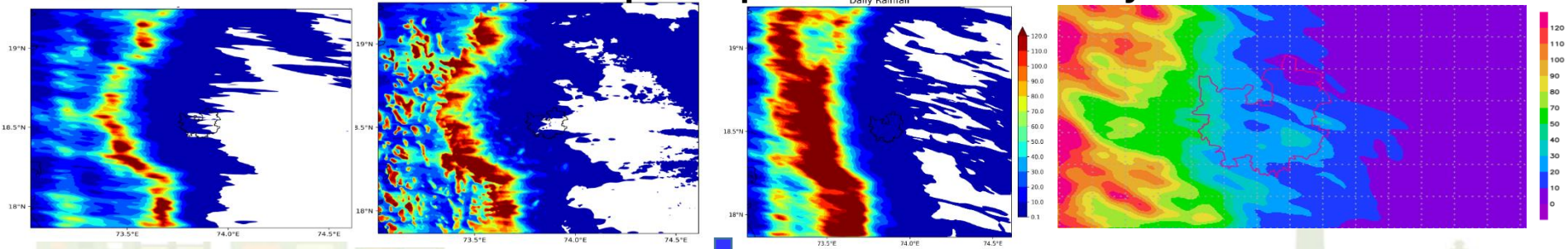
Step 1: Fixed Monsoon and Indian domain



Step 2: multiple domain creation for Pune city



Sample outputs: domain sensitivity



Domain size and location played important roles for cities with complex topography

Kirkwood et al., 2021

Physics Sensitivity

Simulation Number	PBL	Land Surface	Cumulus	Micro-physics
1	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	No CU	Kessler Scheme
2	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	No CU	WRF Single–moment 6–class Schem
3	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	No CU	Thompson Scheme
4	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	No CU	Ferrier (Eta) Scheme
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6	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	Kain–Fritsch Scheme	Kessler Scheme
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11	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	Betts-Miller-Janjic (BMJ)	Kessler Scheme
12	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	Betts-Miller-Janjic (BMJ)	WRF Single–moment 6–class Schem
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16	Mellor–Yamada–Janjic Scheme (MYJ	Unified Noah Land Surface Mode	Multi–scale Kain–Fritsch Schem	Kessler Scheme
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41	Bougeault-Lacarrère (BouLac)	Unified Noah Land Surface Mode	No CU	Kessler Scheme
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45	Bougeault-Lacarrère (BouLac)	Unified Noah Land Surface Mode	No CU	Goddard Scheme

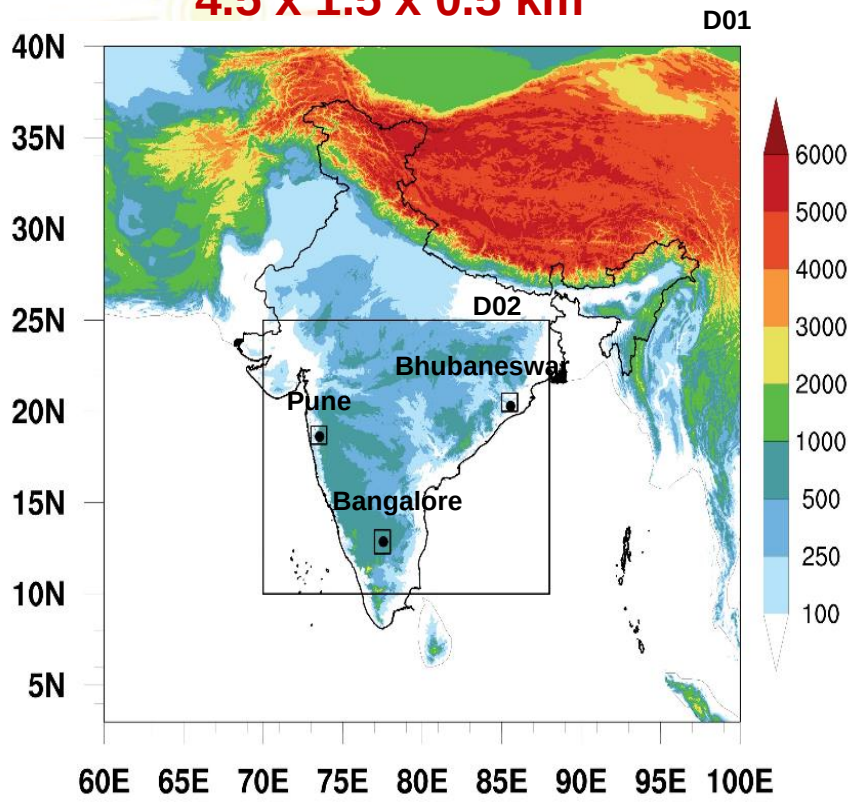
Extensive sensitivity analysis is required for high-resolution simulations

Model Configurations

Experimental setup

Initial and boundary data	NCEP GFS 0.25^{o} , IMD-GFS 0.25^{o}
Resolution	4.5 × 1.5 km and 4.5 × 1.5 × 0.5 km 9 x 3 x 1 km
Horizontal grid system	Arakawa-C grid
Vertical layers (Ptop)	45 sigma levels
Time integration scheme	3rd order Runge-kutta scheme
Spatial differencing scheme	6th order center differencing
Microphysics	WRF Single-Moment 6-class scheme (WSM6)
Radiation scheme	RRTM longwave Goddard shortwave radiation
PBL parameterization	Bougeault–Lacarrere Scheme (BouLac)

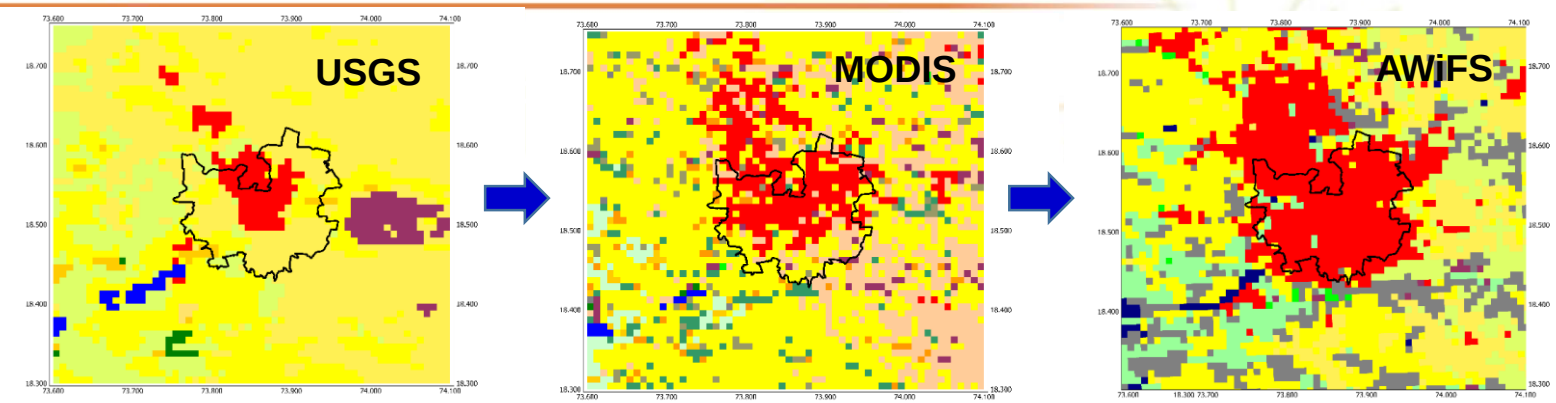
4.5 x 1.5 x 0.5 km



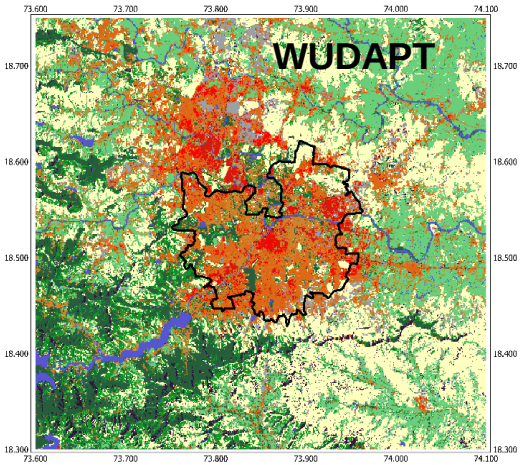
0.5 km – over the city region

Similar approach can be followed for setup of model for any city

City-specific LULC Ingestion



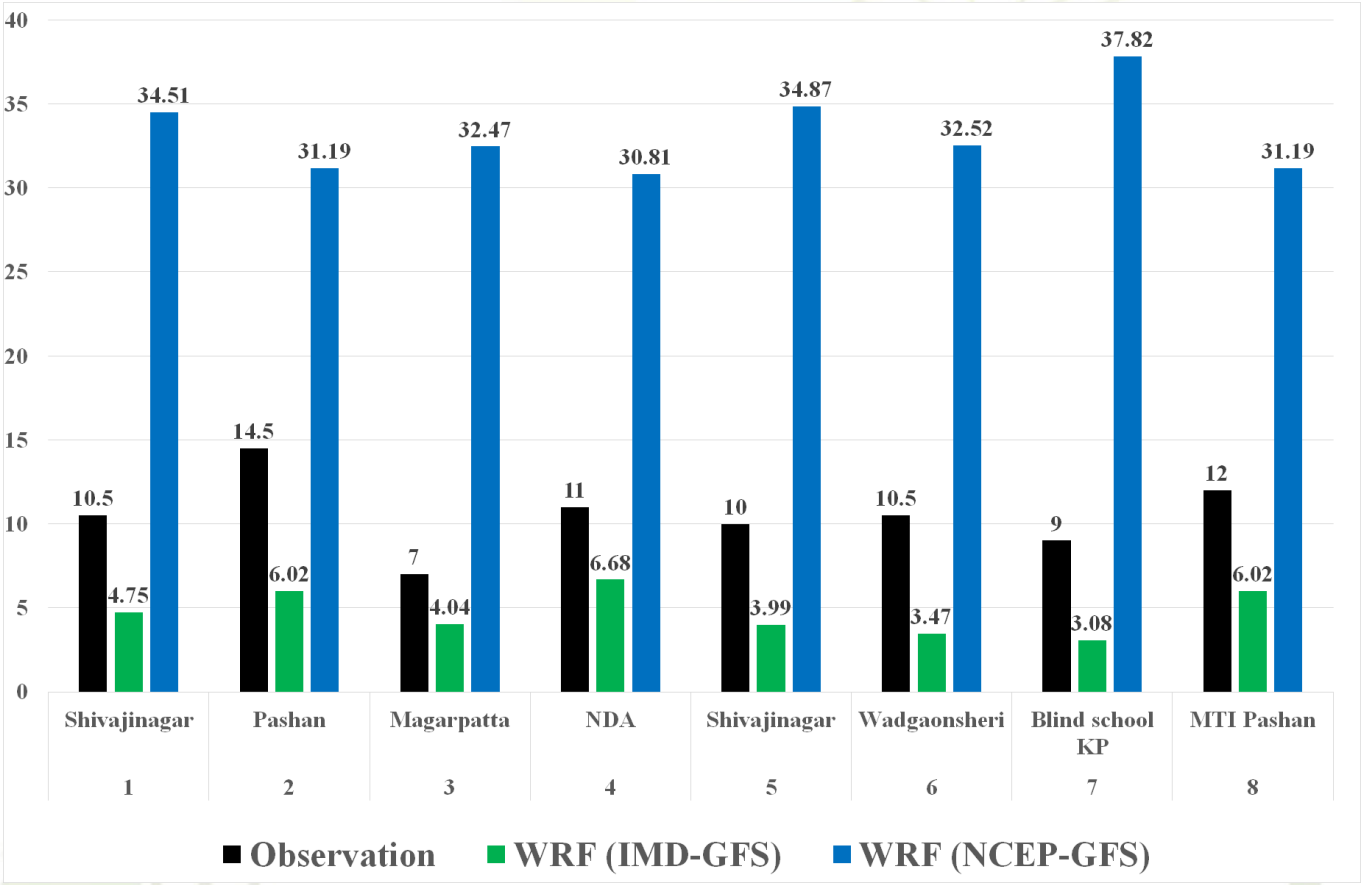
WUDAPT created using real-time Landsat Imagery is more realistic



The use of WUDAPT LCZ and the UCM improved the forecast skill

The high resolution of LULC increases the computational cost by 15-25%, depending on the no. of nested domains (may not be suitable for daily forecast)

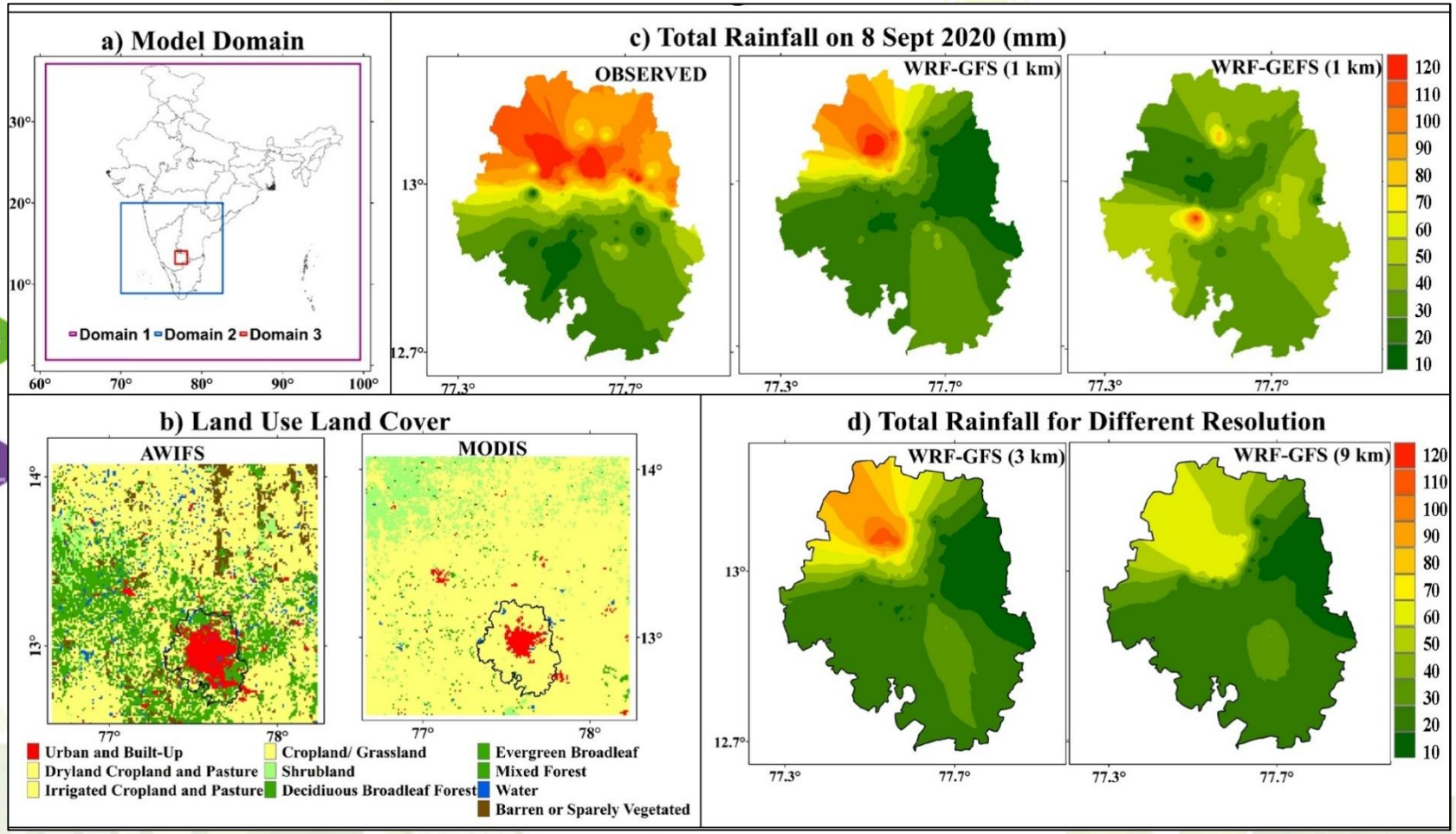
Choose : IC/BC



IMD GFS data improved the rainfall forecast over Pune than NCEP

Bangalore Heavy Rainfall Simulation
8-9 Sept 2020

Resolution – 1x1 km^2



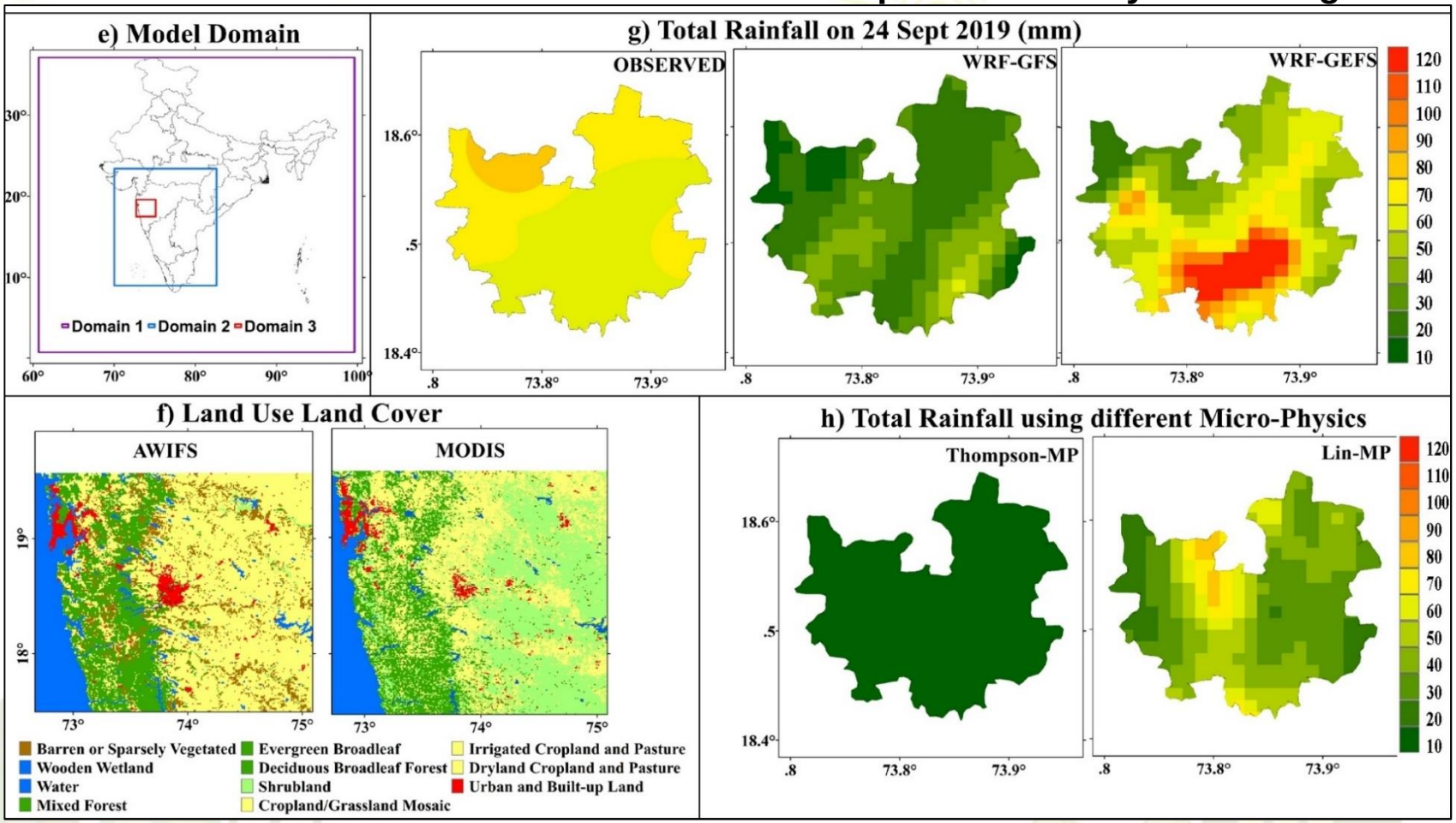
Significance: 1-km domain is able to capture the heavy rainfall signature

Kaginalkar et al., 2022, BAMS, 103

Pune Heavy Rainfall Simulation
24 Sept 2019

Resolution – 1x1 km²

Not able to capture the heavy rainfall signature

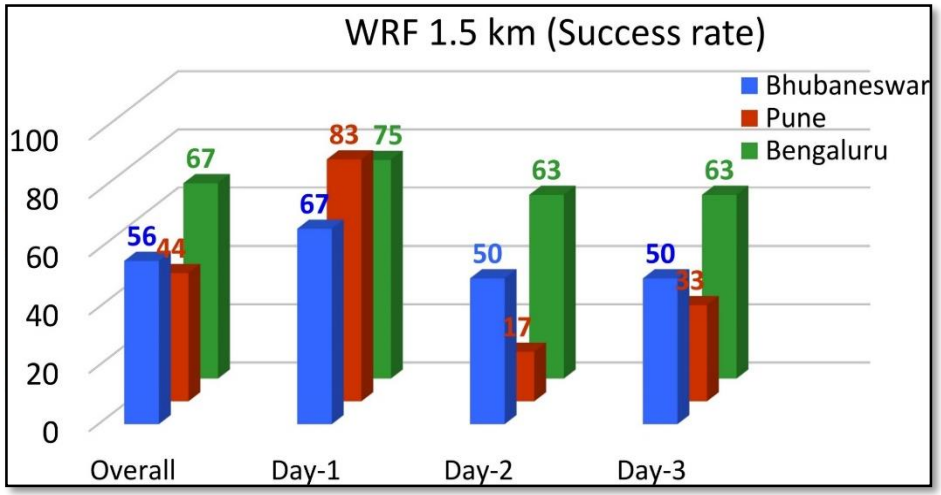


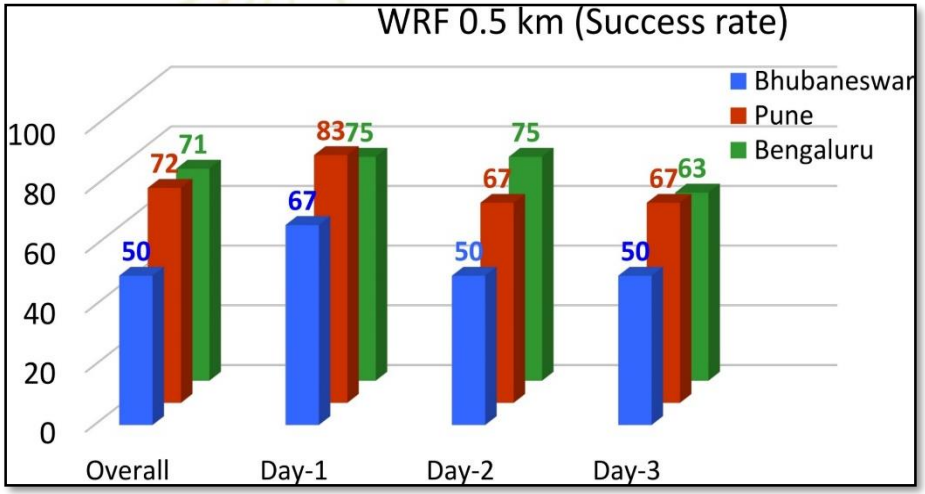
The impact of urbanization on extreme rainfall is nonuniform and highlights the need for continued robust analysis

Kaginalkar et al., 2022, BAMS, 103

Resolution Impact: 1.5 vs 0.5 km

Model Success Rate in percentage (%)



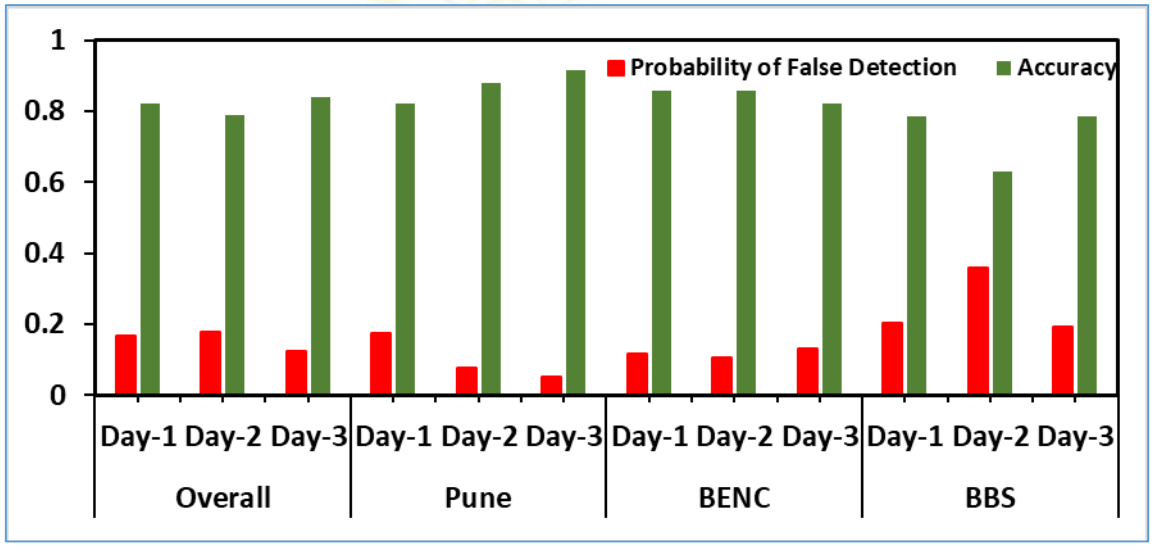


- Significant improvement in the overall "**Success Rates**" using 0.5 km than to 1.5 km
- Improvement more prominent over Pune

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

Categorical skill scores: Monsoon -2022

HRE-2022 (combined)	Accuracy	Probability of detection	Probability of false detection
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**	**Probability of detection**	**Probability of false detection**
*Day-1	0.821	0.750	0.175
Day-2	0.881	0.000	0.075
Day-3	0.917	0.250	0.050
BENC	**Accuracy**	**Probability of detection**	**Probability of false detection**
*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**	**Probability of detection**	**Probability of false detection**
*Day-1	0.786	0.667	0.205
Day-2	0.631	0.500	0.359
Day-3	0.786	0.500	0.192



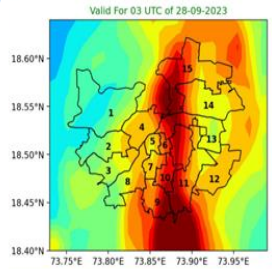
Model - showing better skill in capturing the HRE with less Probability of False Detection (<20%) and more Accuracy (> 63 %)

Summary : Model Skill

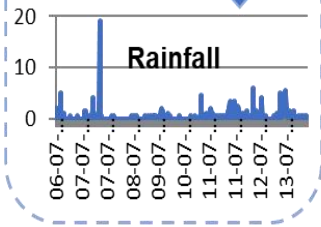
- WRF setup able to capture the Heavy rainfall at city scale
- WRF 0.5 km greater skill than 1.5 km (~ 10-20%)
- The city scale prediction skill of WRF (1.5 km & 0.5 km) significantly higher than the driving GFS IC/BC
- Model stable, giving good indication of occurrence and non-occurrence (Success rate >63%, False alarm <20%)

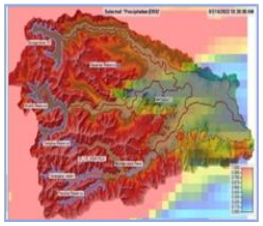
Integrated Coupled Models

Urban Flood Forecasting

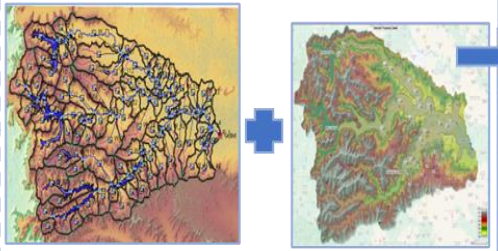


WRF Forecasted Rainfall for Delineated Pune Catchment

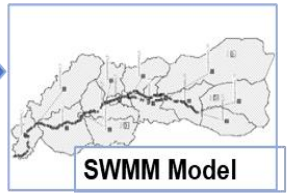




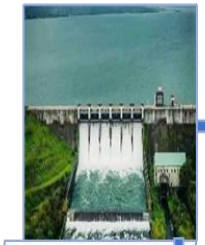
Gridded Rainfall in HEC-RAS



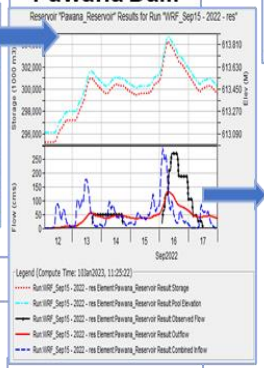
Integrated HEC-HMS and HEC-RAS Model



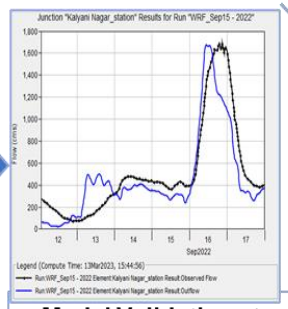
SWMM Model



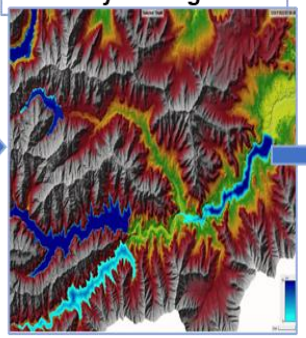
Pawana Dam



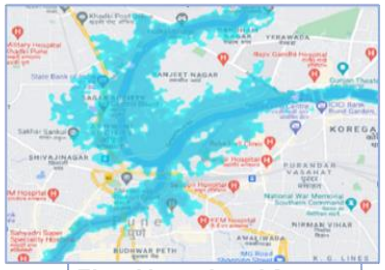
Pawana Reservoir Simulation



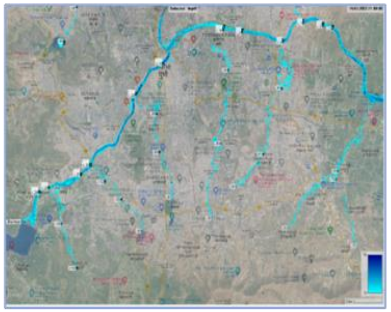
Model Validation at Kalyani Nagar

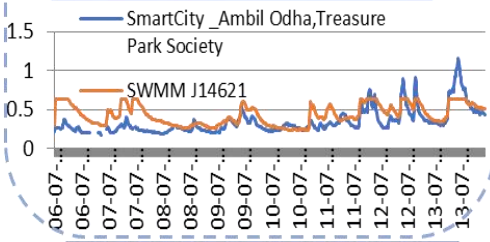


7 Reservoir Operations



Flood Inundated Areas





Flood Visualisation

Integrated Hydro-Met Simulations

Integrated Reservoir Operations

Integrated Hydro-Met Modelling Framework

Pune: 17 Oct 2022 Flood Simulation

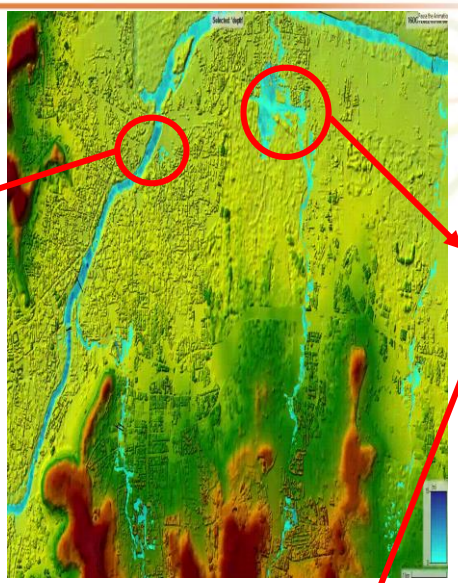
Source: https://www.hindustantimes.com/cities/pune-news/punes-2022-october-rains-three-times-more-than-normal-101667237930940.html

Waterlogging at Mahesh Society Parking Bibwewadi

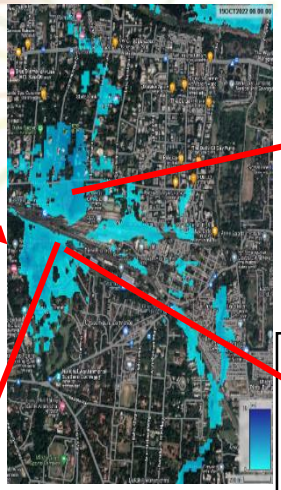
Source: Indian Express

Source: https://indianexpress.com/article/cities/pune/pune-flooding-caused-by-cloud-burst-like-rain-says-pmc-8216771/

Bibawewadi



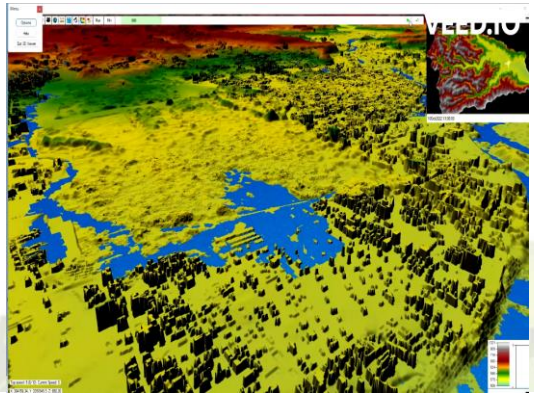
Source: Twitter



Pune Railway Station

Source: Twitter

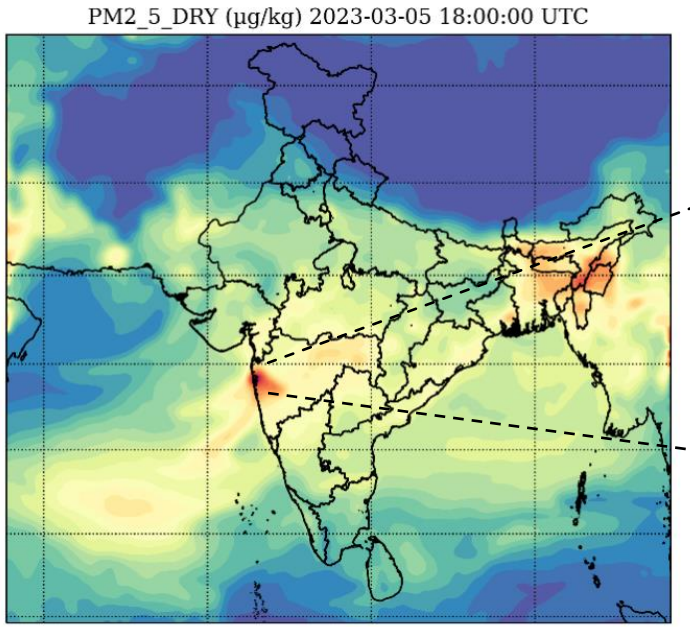
In some low-lying areas, vehicles were submerged in rainwater. In fact, the railway station, too, was experiencing flash floods

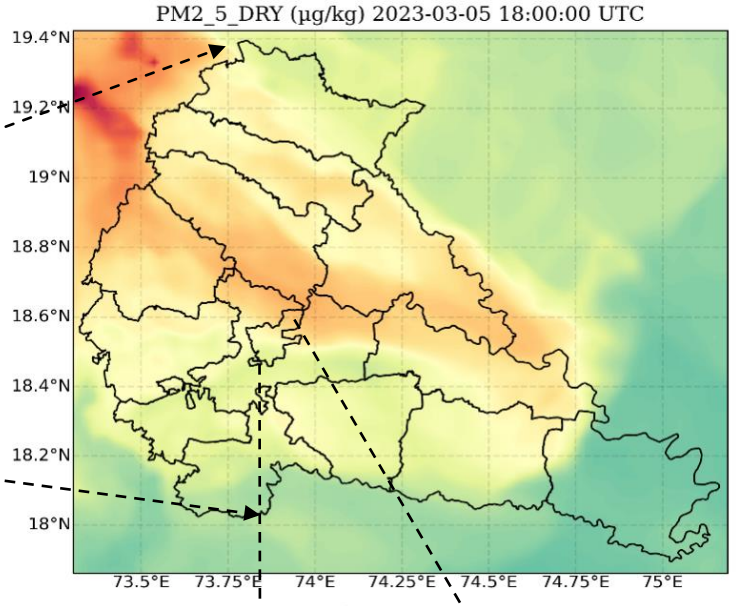


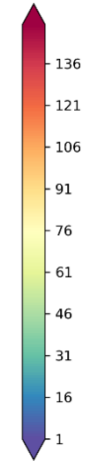
Towards 3D Digital Twins

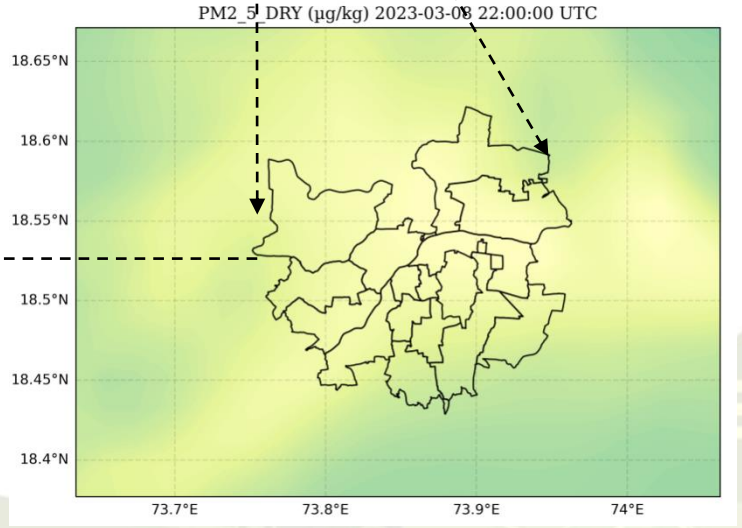
Pune Air Quality Early Warning System

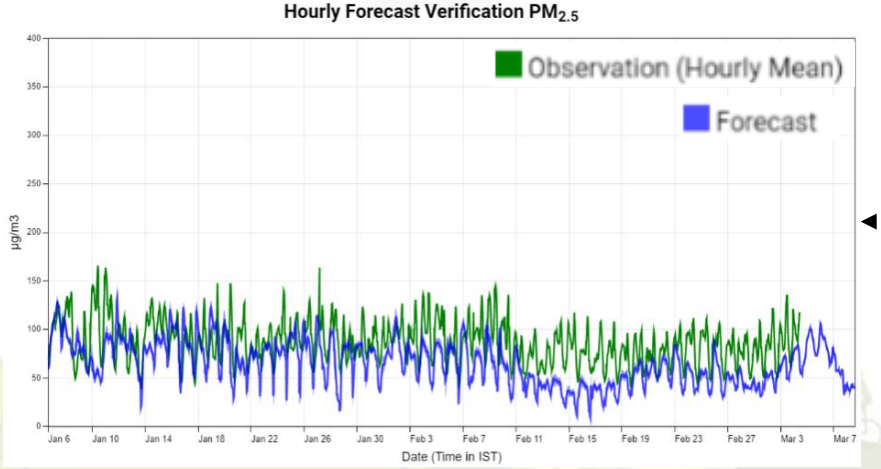
AQ forecast shared daily with PMC





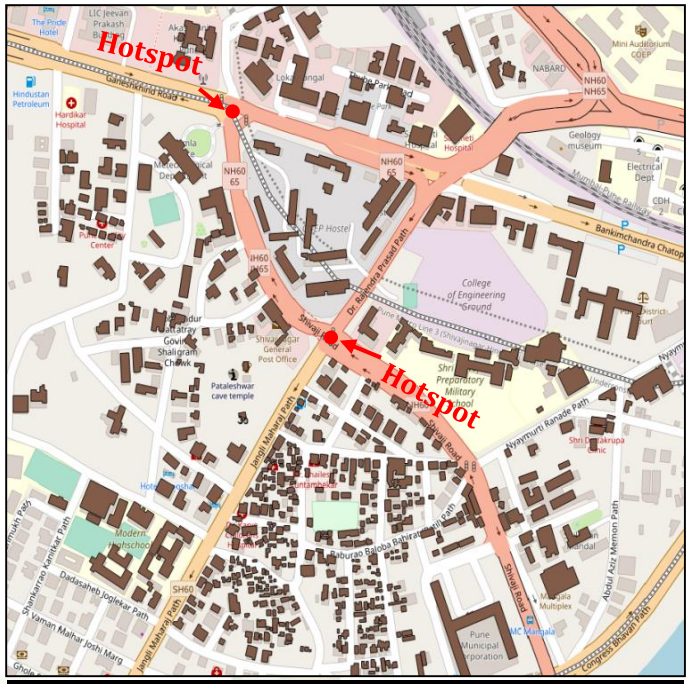




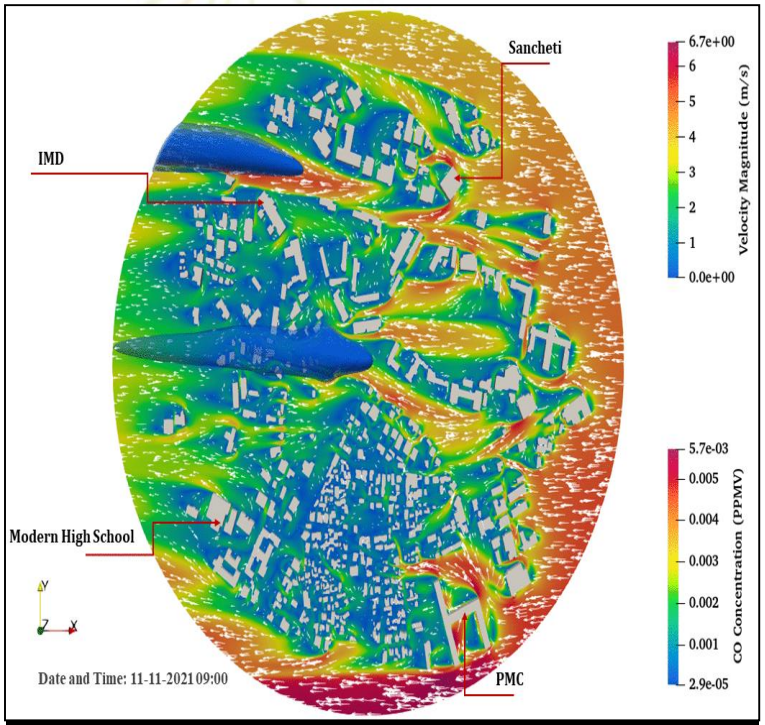


Pollutant Dispersion

Coupled WRF-Chem and OpenFOAM (CFD) modeling set-up for micro-level dispersion of pollutants over pollution hotspot



Shivaji Nagar Area with two hotspots



Spread of CO over Shivaji Nagar

CFD Model took ~36 hours of computing time for 1-day simulation (resolution 10-m) for single pollutant (with 20 nodes; 960 cores)

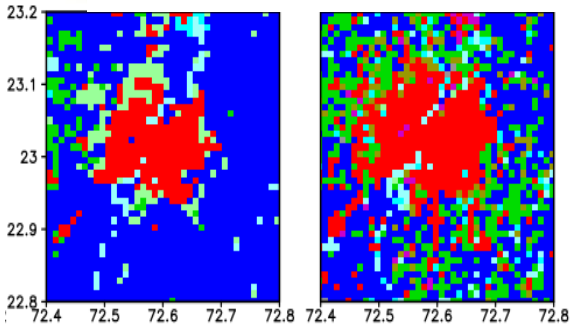
Urban Heat Island

Urban Heat Island: Impact of Urbanization

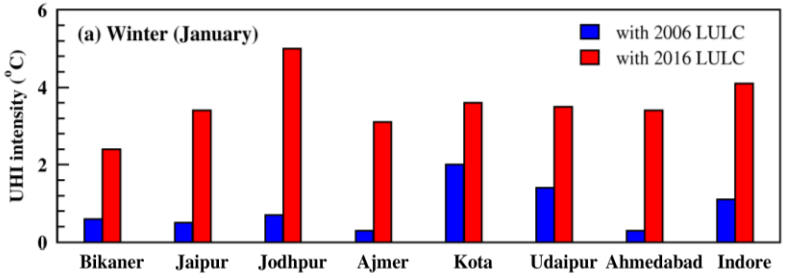
Objective: To quantify the impact of urbanization on surface meteorology and UHI over major urban cities in NE India

1. Ahmedabad
2. Bikaner
3. Jaipur
4. Indore
5. Ajmer
6. Kota
7. Udaipur
8. Jodhpur

Ahmedabad LULC 2006 vs 2016

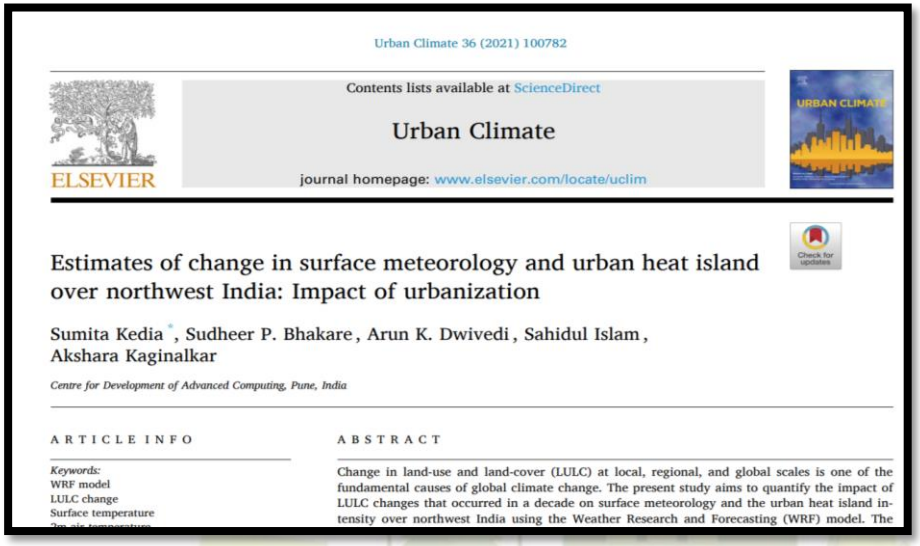


UHI intensity: Impact of urbanization



Outcome:

- A significant increase in near-surface temperature is observed
- Area of higher temperature zones has increased due to urban expansion
- Night-time averaged UHI has increased over all the cities



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ELSEVIER

Estimates of change in surface meteorology and urban heat island over northwest India: Impact of urbanization

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ARTICLE INFO

Keywords:
WRF model
LULC change
Surface temperature

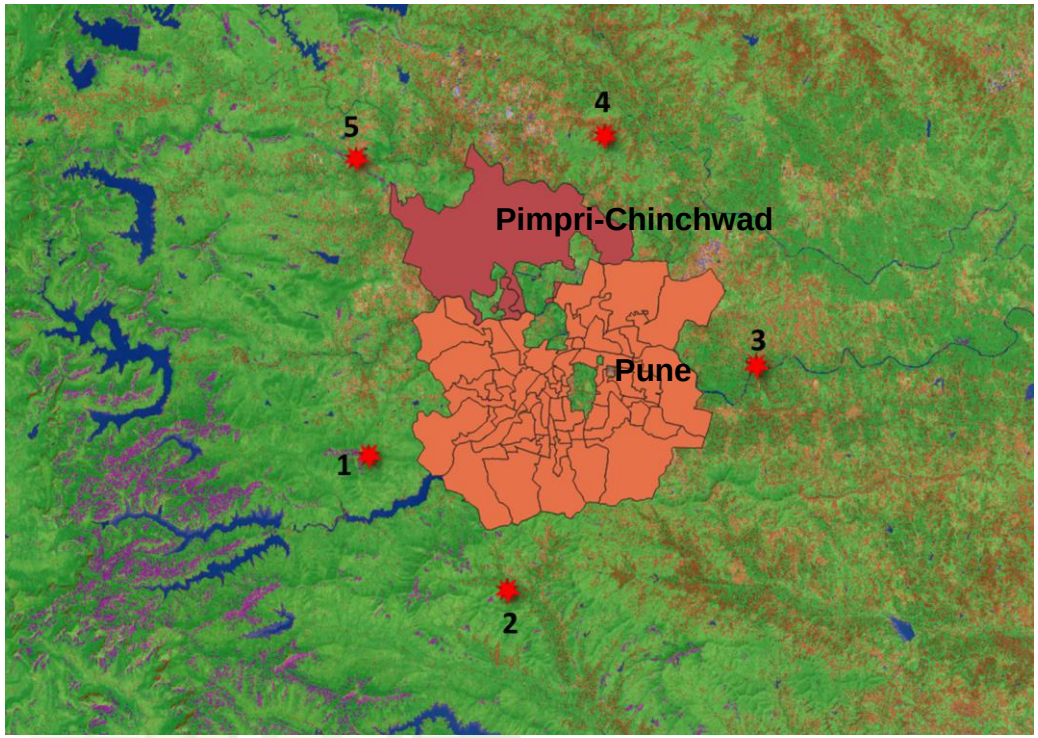
ABSTRACT

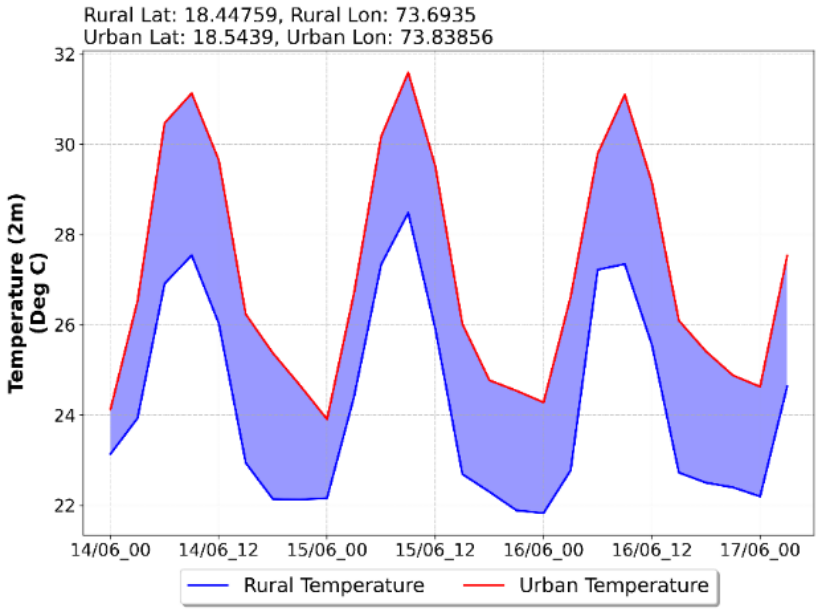
Change in land-use and land-cover (LULC) at local, regional, and global scales is one of the fundamental causes of global climate change. The present study aims to quantify the impact of LULC changes that occurred in a decade on surface meteorology and the urban heat island intensity over northwest India using the Weather Research and Forecasting (WRF) model. The

Urban Heat Island

Criteria for Identification of Rural Location

1. NDVI > 0.5
2. Rural area > 5 km & < 10 km from city boundary





Urban area is the city center

Rural area - as the location where the temperature difference is maximum

Web-based - Integrated System

Issues faced by Students and Young Researchers / Scientists

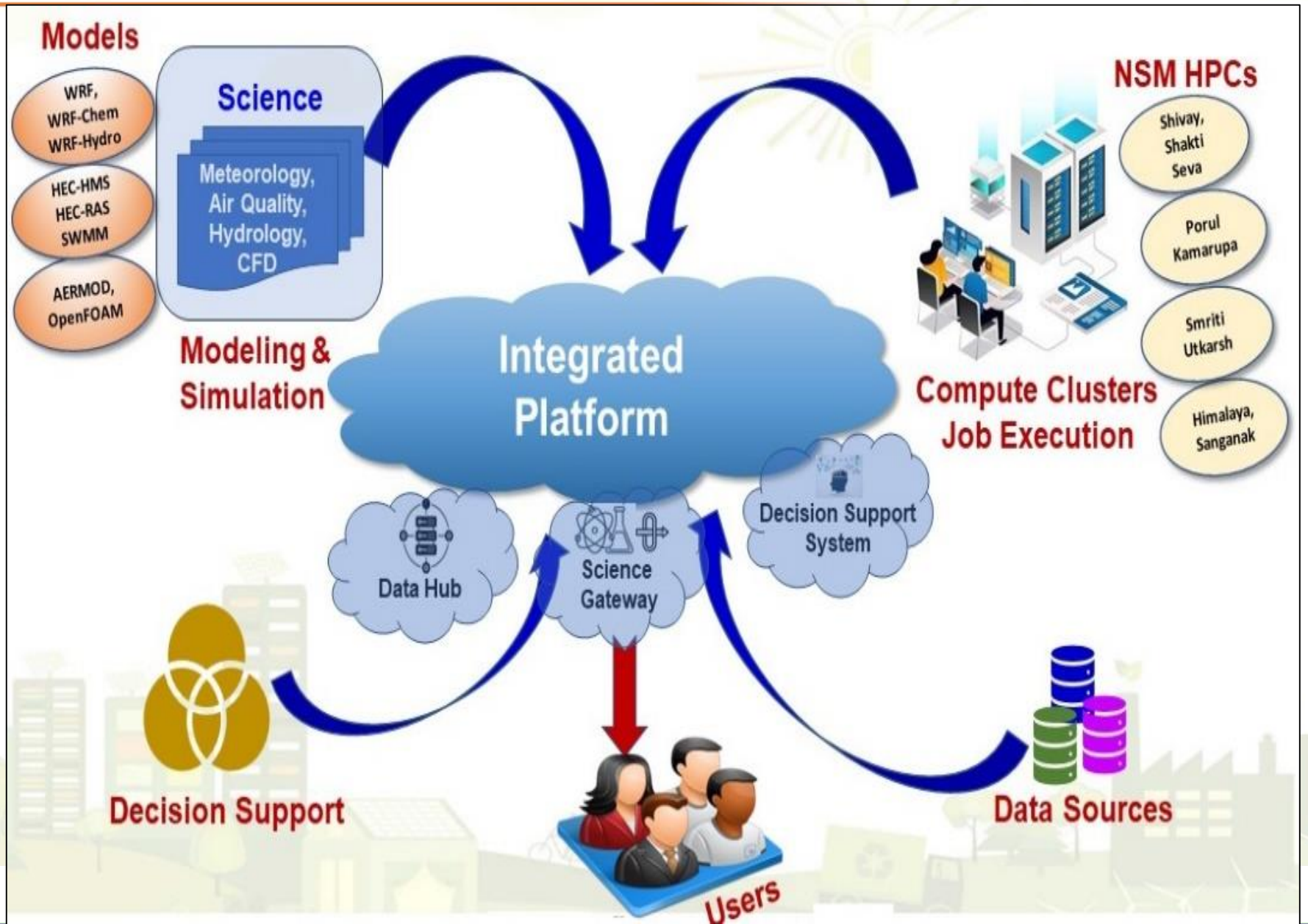
- knowledge of Linux/Unix system
- To know Compilers
- Libraries/model installation on Linux environment
- Data handling
- Visualization of the outputs

Web-based - Integrated System

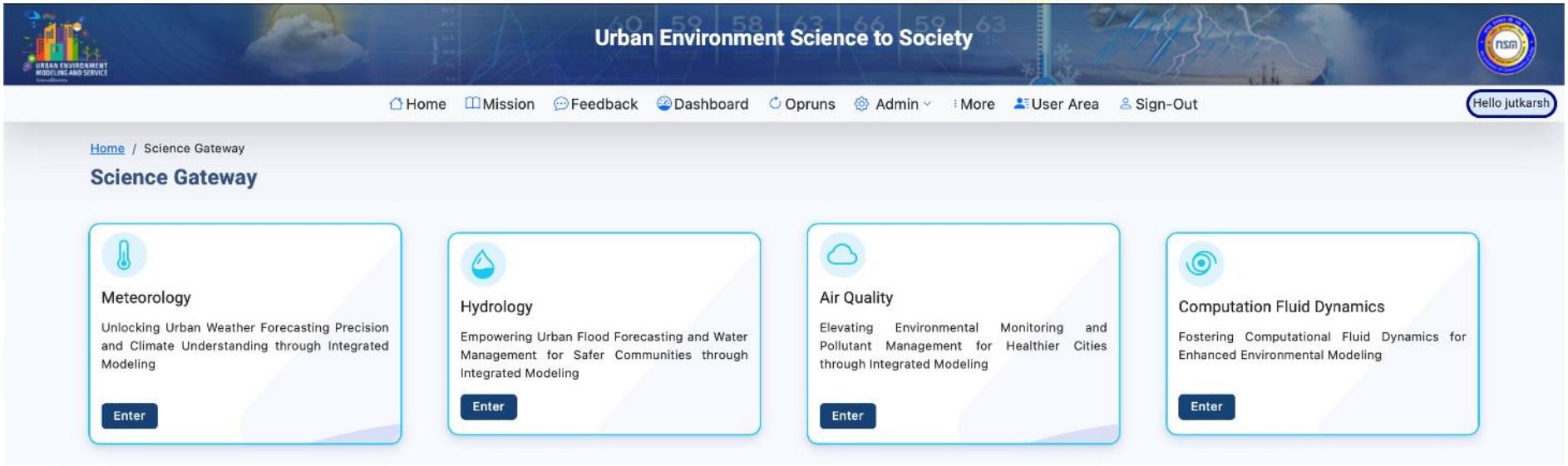
Integrated platform for

- Data Accusation
- Modeling and Simulation
- Postprocessing
- Visualization of products
- Decision Support System

Automated Model framework



GUI-based Automated Model Execution



WRF

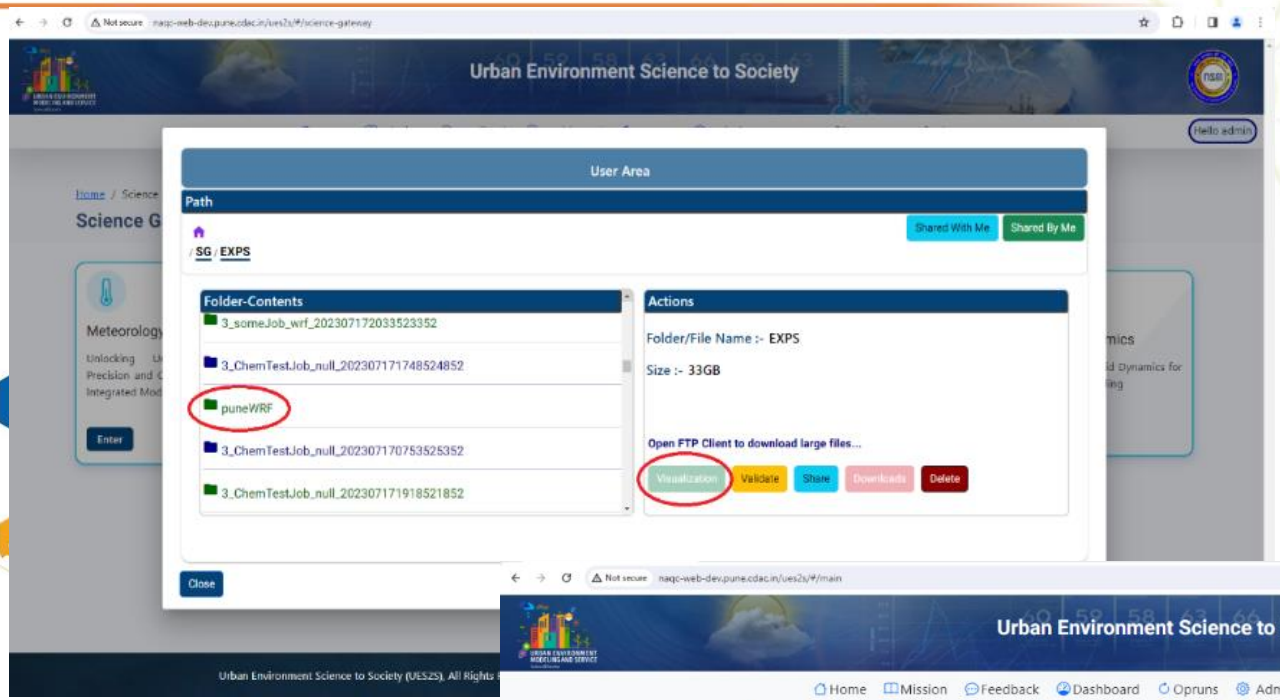
HEC-RAS
HEC-HMS
SWMM

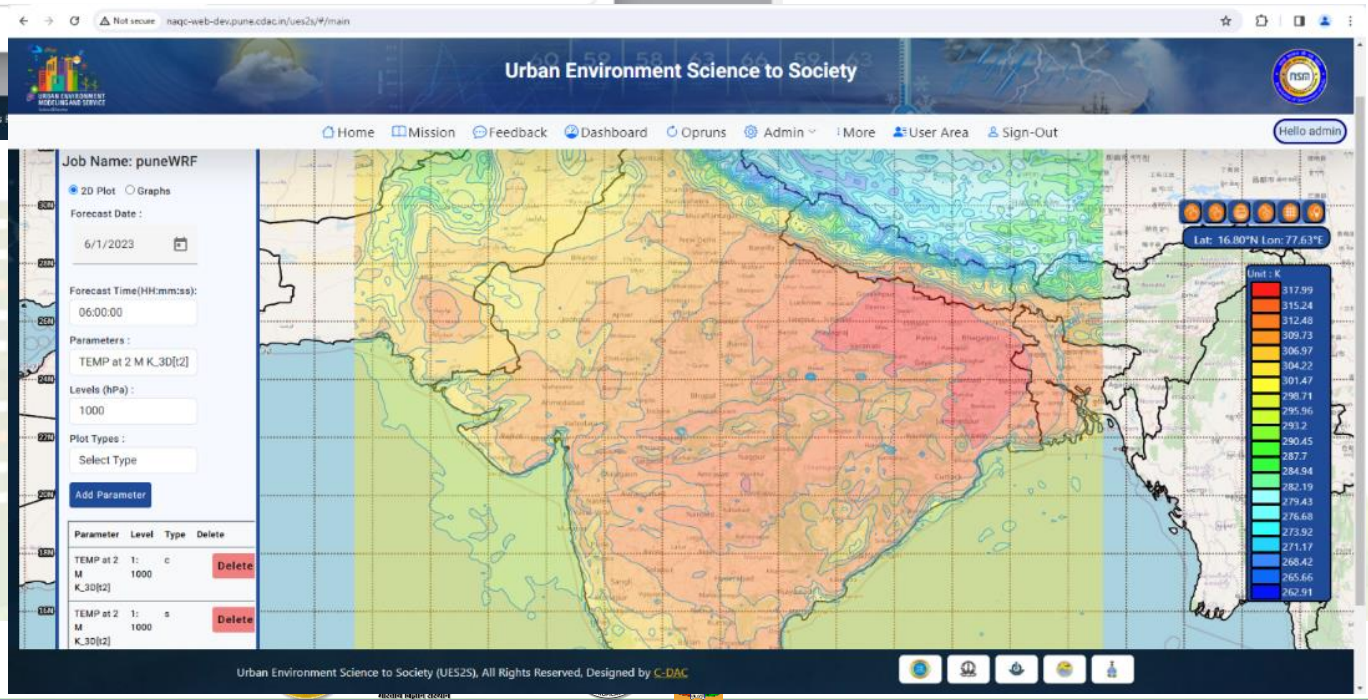
WRF-Chem
AERMOD
CALPUFF

OpenFOAM

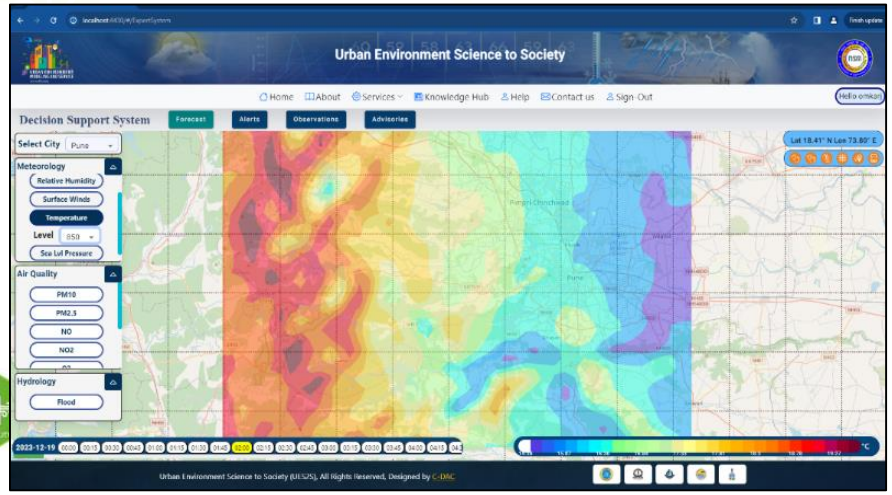
These standalone and Coupled models can be executed using GUI based framework by following a few steps

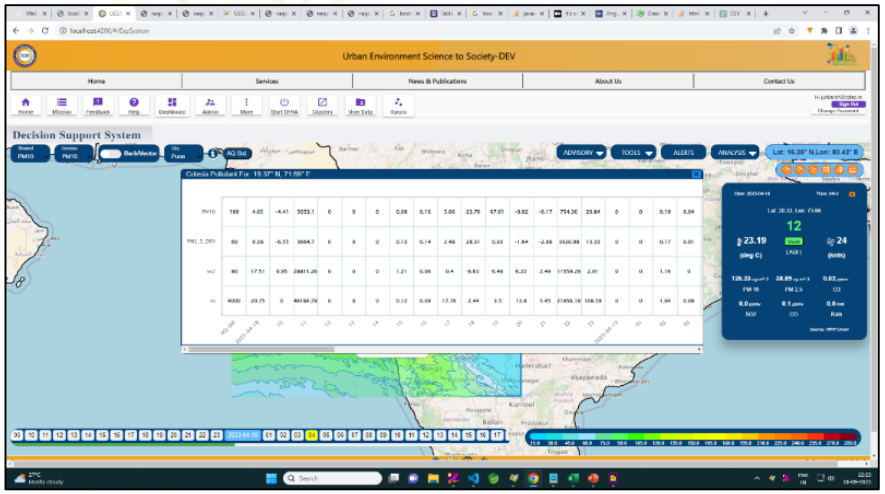
Model Output Visualization

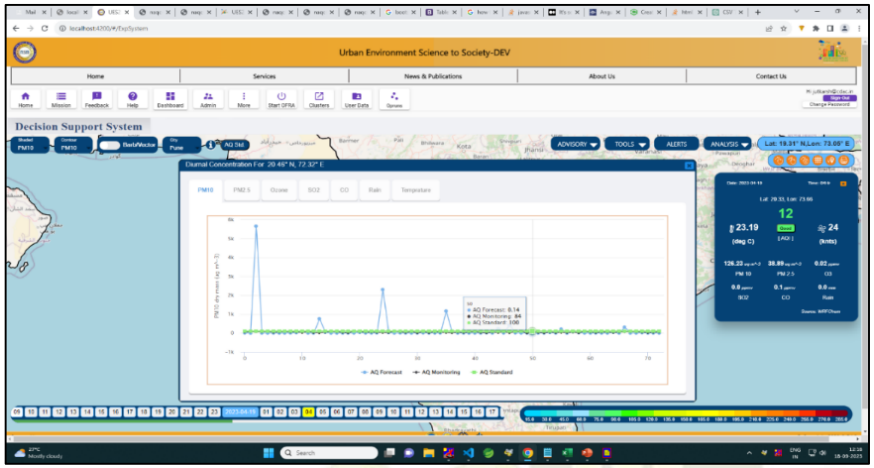




Integrated Decision Support System



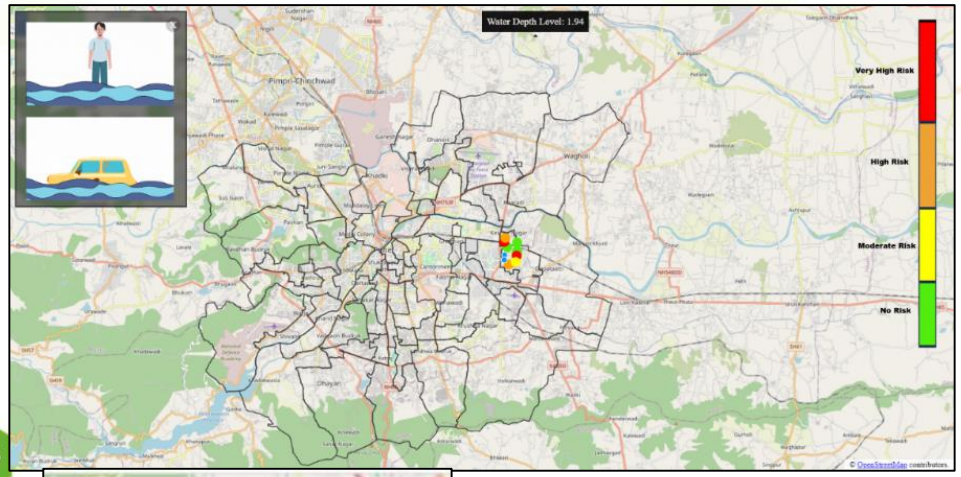




Features: MET & AQ

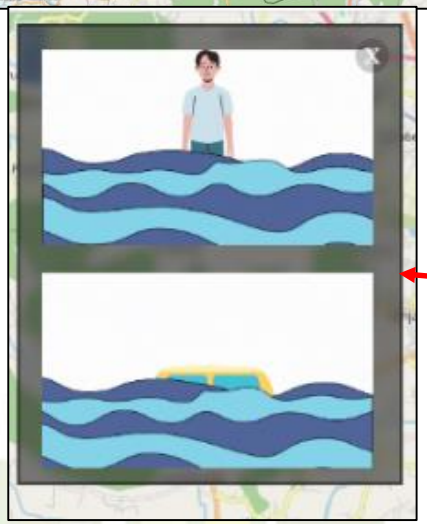
- Weather and Air Quality hourly forecast
- Ward wise forecast products
- Alerts – Heavy rainfall, thunderstorms, high AQI
- Heatwave alerts, advisory
- Scenarios generation
- User role-based functionality
- Information dissemination to stakeholders & public

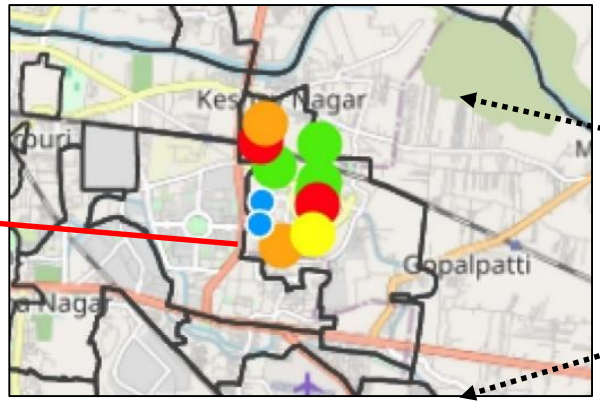
Integrated Decision Support System

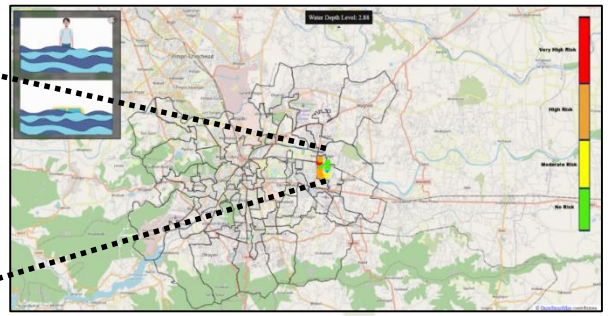


Features: Hydrology DSS

- Flood inundation info at ~15-minute interval
- Visual Flood Risk Alert and Advisory
- Water spread animation
- Information dissemination to stakeholder public

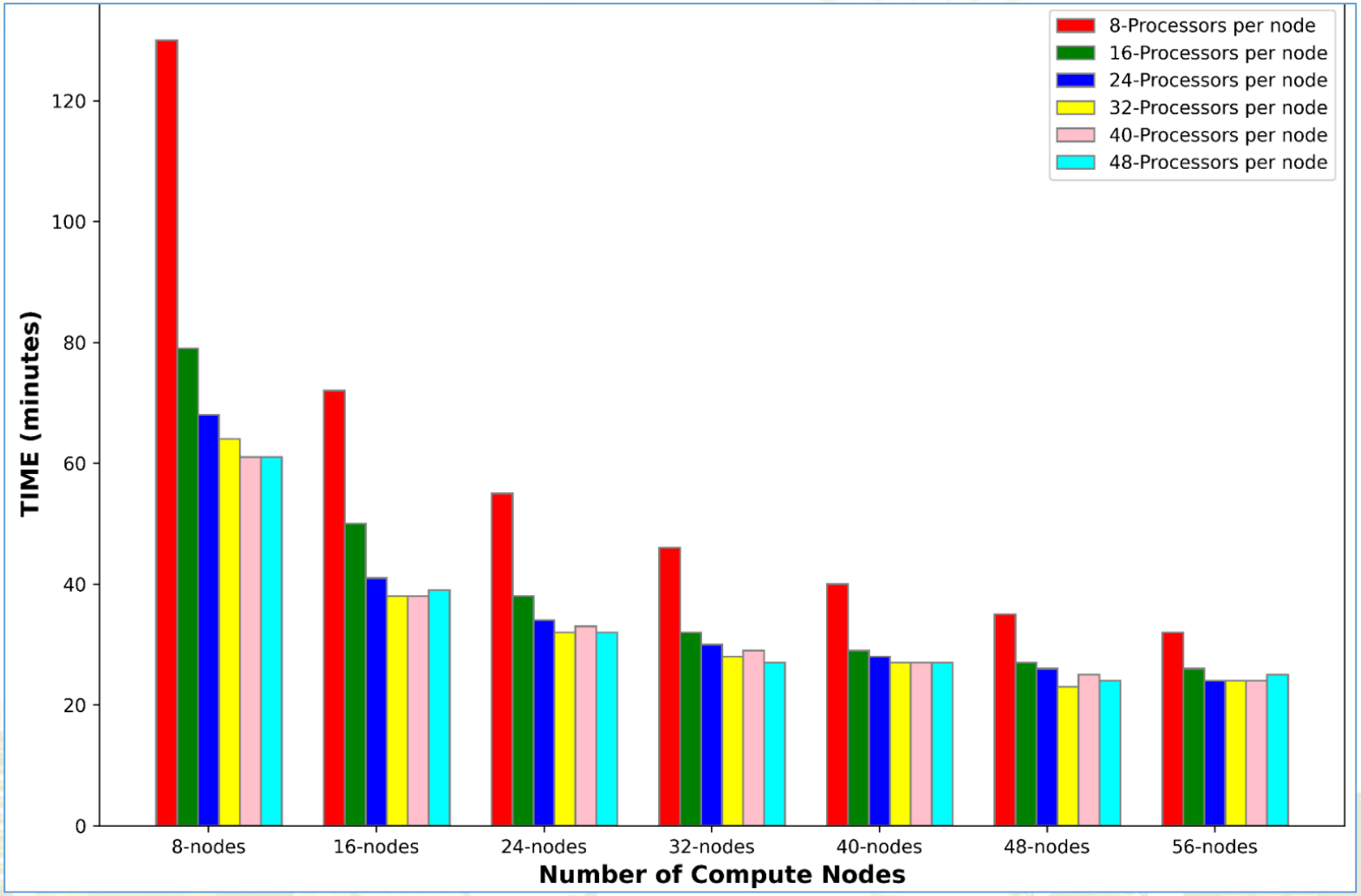






Computational Optimization

Model Optimization: Computational



WRF: Identify the optimal no. of nodes daily simulation

WRF Model Optimization

Compute Node optimization:

Nodes (cores)	Time for WRF run in minutes
10 (480)	705
20 (960)	410
30 (1440)	267
40 (1920)	252

Simulation time optimization:

a. GFS data downloading

b. WRF model run - I/O limitation, and model integration time step

c. Time reduction in post-processing using ARWpost in parallel mode

HPC System (Param Smriti)	Total Core	GFS Data Downloading	Pre-processing Time	Time for wrf.exe	Post-Processing Time	Total Time
Before Optimization	1440	35 m	42m	267m	28 m	372 m
After Optimization	1440	2m	32	210 m	1 m	245m

WRF Model Optimization: Ensemble

Sl. No.	PBL	LSM	Cumulus	Microphysics
EnsMember-1 (EM1)	BouLac	Unified Noah LSM	No Cu	WSM-6
EM2	BouLac	Unified NoaH	No Cu	Lin
EM3	BouLac	Unified NoaH	No Cu	Ferrier
EM4	BouLac	Noah – MP LSM	KF	Ferrier

Ensemble	No. of cores	Time taken (minutes)	Output storage
EM1	1920 (40 Nodes)	11.6 hours	173 GB
EM2	1920	11.6 hours	163 GB
EM3	1920	11.6 hours	173 GB
EM4	1920	11.6 hours	170 GB

Identified the complexities of running the ensemble runs

Urban Modeling – Challenges/Solutions

- Challenges to define a multidisciplinary approach, combining advanced modeling techniques, comprehensive data collection, and collaboration between multi-institutes – **Collaborative System in place**
- **Data Acquisition**: Gathering detailed and accurate data for urban areas, essential for model validation – **Developed DataHub**
- **Computational Barriers**: The computational demands of urban modeling, especially when using a CFD model **- Ongoing**
- **Model Structural Uncertainty**: Significant uncertainty in the structural aspects of models when simulating urban rainfall **– Working further**
- Urban planners, and policymakers to improve the accuracy and utility of urban scale modeling **– DSS developed**

Cloud Services

Science Gateway
Model-as-a-Service

- HPC based Automated Model Execution Workflows
- Meteorology, Hydrology, Air Quality, CFD & Coupled models
- Integrated 2D & 3D Data Visualization

Decision Support System
Software-as-a-Service

Decision Support System

- Air Quality
- Meteorology
- Hydrology
- User specific data

Data Hub
Data-as-a-Service

- Big Data framework – Data storage & dissemination
- Integrated Data Analytics

Services

User-friendly interface for weather, hydrology, and air quality modeling for research and operational

Automatic model framework:

- A user-friendly multi-modeling platform
- The researcher should focus on the science part only …rest should be taken care

DataHub: database management

- Single source for all model-related data from different sources in one place
- Easy-to-use search/view/download options

Validation and verification tools:

- Useful to cross-check forecast quality against observations
- Easy-to-use tool for model verification and validation
- All basic and advanced statistical parameters at one place

DSS:

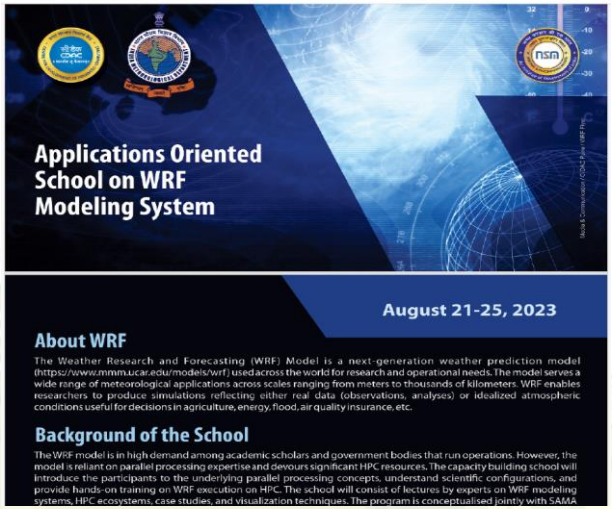
- Identify various critical factors, hots spots, possibility of weather related events
- Define methods and rules for the implementation of the assessment
- Analyse the impact of actions

Visualization: 2D/3D

A User-friendly platform to select and visualise any parameters in the required way

Capacity Building:
Modeling and Simulation

- WRF Training: Along with SAMA for South Asian countries – **April 2023** **(online; 120+ participants)**
- Applications oriented training school conducted at C-DAC Pune (**21-25 Aug 2023**) **(offline; 44 participants)**
  - There were 44 participants from across the country – **25 Institutes across India**
  - Expert lectures taken by C-DAC Pune, IMD, IITM, NIT, and industry scientists
  - Practical Session conducted – Basic to Advanced level



NSM - PARAM Utkarsh HPC - Login given

Acknowledgement

- India Meteorological Department (IMD)
- National Data Centre, IMD Pune
- NCMRWF IMDAA and NCUM data
- NSM (MeitY)
- NSM HPC resources
- Water Resource Department Govt. of Maharashtra
- Pune Municipal Corporation and Pune Smart City
- Karnataka State Natural Disaster Monitoring Centre (KSNDMC)
- Bruhat Bengaluru Mahanagara Palike (BBMP)
- Bangalore Development Authority (BDA)
- Central Pollution Control Board (CPCB)
- Environmental Science Department, SPPU, Pune
- Smart City administrations (IUDX data)
- Orissa State Pollution Control Board (OSPCB)
- Commission for Air Quality Management

Thank you