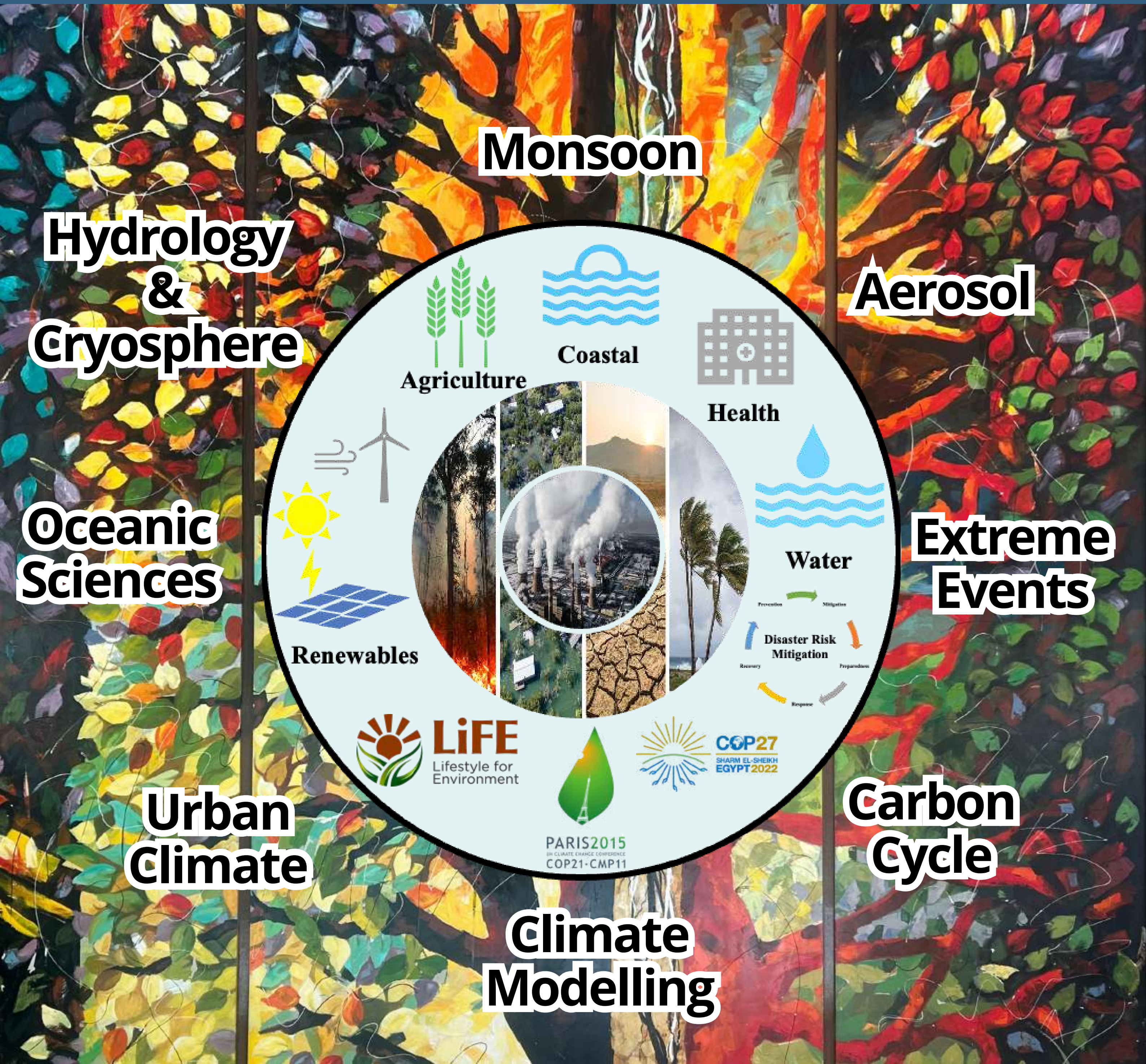
Ministry of Earth Sciences
GOVERNMENT OF INDIA

विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF SCIENCE & TECHNOLOGY

India's Climate Research Agenda: 2030 and beyond



Edited by Dr. Akhilesh Gupta and Dr. Subimal Ghosh

Editors

AKHILESH GUPTA
Science and Engineering Board
Department of Science & Technology
Ministry of Science & Technology
Government of India
New Delhi, India

SUBIMAL GHOSH
Interdisciplinary Programme in Climate Studies
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India

Coordinating Lead Authors

ARINDAM CHAKRABORTY
Centre for Atmospheric and Oceanic Sciences
Indian Institute of Science (IISc) Bangalore

PANKAJ KUMAR
Department of Earth and Environmental Sciences
Indian Institute of Science Education and Research (IISER) Bhopal

SRINIVASA KUMAR TUMMALA
Indian National Centre for Ocean Information Services (INCOIS) Hyderabad
Ministry of Earth Sciences (MoES), Government of India

V VINOJ
School of Earth, Ocean, and Climate Sciences
Indian Institute of Technology (IIT) Bhubaneshwar

SANDEEP PATTNAIK
School of Earth, Ocean, and Climate Sciences
Indian Institute of Technology (IIT) Bhubaneshwar

RAJESH KUMAR MALL
DST-Mahamana Centre of Excellence in Climate Change Research
Institute of Environment & Sustainable Development, Banaras Hindu University

VIMAL MISHRA
Department of Civil Engineering
Indian Institute of Technology (IIT) Gandhinagar

MANISH KUMAR GOYAL
Department of Civil Engineering
Indian Institute of Technology (IIT) Indore

H S HOSALIKAR
India Meteorological Department (IMD), Pune

Lead Authors

SUNEET DWIVEDI
Centre of Atmospheric and Ocean Studies
University of Allahabad

R KRISHNAN
Indian Institute of Tropical Meteorology (IITM) Pune

A K SAHAI
Indian Institute of Tropical Meteorology (IITM) Pune

V S PRASAD
National Centre for Medium Range Weather Forecasting (NCMRWF) Noida
Ministry of Earth Sciences (MoES), Government of India

SAROJ KANTA MISHRA
DST Centre of Excellence in Climate Modelling
Centre for Atmospheric Sciences
IIT Delhi

S A SANNASIRAJ
Department of Ocean Engineering
Indian Institute of Technology (IIT) Madras

ABHISHEK CHATTERJEE
Indian National Centre for Ocean Information Services (INCOIS) Hyderabad
Ministry of Earth Sciences (MoES), Govt. of India

SAGNIK DEY
Centre for Atmospheric Sciences
Indian Institute of Technology (IIT) Delhi

M V RAMANA MURTHY
National Centre for Coastal Research (NCCR)
Ministry of Earth Sciences (MoES), Government of India

V GEETHALAKSHMI
Tamil Nadu Agricultural University, Coimbatore

UDIT BHATIA
Kiran C Patel Centre for Sustainable Development
Indian Institute of Technology (IIT) Gandhinagar

ASHWIN SESHADRI
Divecha Centre for Climate Change & Centre for Atmospheric and Oceanic Sciences
IISc Bangalore

RAJESH KUMAR
School of Earth Sciences
Central University of Rajasthan

ANIL KUMAR GUPTA
National Institute of Disaster Management (NIDM), New Delhi

SUBHANKAR KARMAKAR
Interdisciplinary Programme in Climate Studies
Environmental Science & Engineering Department
Indian Institute of Technology Bombay

ANEESH LOTLIKER
Indian National Centre for Ocean Information Services (INCOIS) Hyderabad
Ministry of Earth Sciences (MoES), Govt. of India

FRANCIS P A
Indian National Centre for Ocean Information Services (INCOIS) Hyderabad
Ministry of Earth Sciences (MoES), Govt. of India

SWARUP DANGAR
PhD Scholar
IIT Gandhinagar

Reviewers

S K DASH
IIT Delhi

R KRISHNAN
IITM Pune

ANIL V KULKARNI
Divecha Center for Climate Change
Indian Institute of Science Bangalore

ASHOK KARUMURI
University of Hyderabad

U C MOHANTY
IIT Bhubaneshwar

P P MUJUMDAR
Indian Institute of Science Bangalore

GUFRAN BEIG
National Institute of Advanced Studies
Bengaluru

B S MURTY
Indian Institute of Technology
Madras

N H RAVINDRANATH
IISc Bangalore

DEV NIYOGI
University of Texas, Austin, USA

CHANDRA SHEKHAR JHA
National Remote Sensing Centre

P VINAYCHANDRAN
IISc Bangalore

RAGHU MURTUGUDDE
University of Maryland & IIT Bombay

K J RAMESH
India Meteorological Department

SHAILESH NAYAK
National Institute of Advanced Studies
Bengaluru

A K SAHAI
Indian Institute of Tropical
Meteorology (IITM) Pune

AJIT TYAGI
South Asian Meteorological
Association

डॉ0 जितेन्द्र सिंह
राज्य मंत्री (स्वतंत्र प्रभार),
विज्ञान एवं प्रौधोगिकी मंत्रालय;
राज्य मंत्री (स्वतंत्र प्रभार) पृथ्वी विज्ञान मंत्रालय;
राज्य मंत्री, प्रधान मंत्री कार्यालय;
राज्य मंत्री कार्मिक, लोक शिकायत एवं पेंशन मंत्रालय;
राज्य मंत्री परमाणु ऊर्जा विभाग तथा
राज्य मंत्री अंतरिक्ष विभाग
भारत सरकार

सत्यमेव जयते

Dr. JITENDRA SINGH
Minister of State (Independent Charge)
of the Ministry of Science and Technology;
Minister of State (Independent Charge)
of the Ministry of Earth Sciences;
Minister of State in the Prime Minister's Office;
Minister of State in the Ministry of Personnel,
Public Grievances and Pensions;
Minister of State in the Department of Atomic Energy and
Minister of State in the Department of Space
Government of India

MESSAGE

Green House Gas emission during last century has resulted in unusual global warming, leading to the occurrence of various extreme events with a severe impact on various sectors, such as health, agriculture, food, water, air, biodiversity, etc. Today, climate resilience has become a pre-requisite for smooth Economic development of a nation. Hence, an inclusive approach is needed to strengthen the vulnerable communities of a nation along with the protection, conservation and sustainable use of the available natural resources.

In the recent past, India has showcased its significant contribution in the area of climate impacts, adaptation, and mitigation. The country has proved its enormous scientific potential in the international scientific literature and climate services, including monitoring and forecasting systems. Hence, to become a global leader in climate science, identification of a focused research pathway and set targets for 2030 and beyond are the need of the hour which will accelerate the country's efforts to achieve its net zero emission target by 2070.

The report entitled "India's Climate Research Agenda: 2030 and Beyond" identifies the major themes for Climate Science and Adaptation, such as monsoon, climate modelling, aerosol-climate interactions, hydrology & cryosphere, extreme events, oceanic sciences, urban climate, carbon cycle and sector-specific climate services. The lead authors of the report have come out with a detailed assessment of the research findings by the scientists, existing gaps, and possible pathways to bridge in the gaps. I congratulate the editors and contributors for this visioning exercise to enable climate resilience across the nation. I must compliment hard work carried out by Dr. Akhilesh Gupta, Senior Advisor & Chairman of Drafting Committee of the report.

I am confident the report will be of great value to the climate researchers, students, and policy makers in designing a vision for climate studies for future.

(Dr. Jitendra Singh)
MBBS (Stanley, Chennai)
MD Medicine, Fellowship (AIIMS, NDL)
MNAMS Diabetes & Endocrinology

Anusandhan Bhawan, 2, Rafi Marg
New Delhi-110001
Tel. : 011-23316766, 23714230,
Fax. : 011-23316745

South Block, New Delhi-110011
Tel. : 011-23010191 Fax : 011-23017931
North Block, New Delhi-110001
Tel. : 011-23092475 Fax : 011-23092716

सत्यमेव जयते
डॉ. एस. चंद्रशेखर
Dr. S. Chandrasekhar

सचिव
भारत सरकार
विज्ञान एवं प्रौद्योगिकी मंत्रालय
विज्ञान एवं प्रौद्योगिकी विभाग
Secretary
Government Of India
Ministry of Science and Technology
Department of Science and Technology

G20 2023 INDIA
वसुधैव कुटुम्बकम्
ONE EARTH • ONE FAMILY • ONE FUTURE

आज़ादी का अमृत महोत्सव

23rd May, 2023

MESSAGE

Climate Change has become a global crisis due to increased frequency and intensity of the extreme events. The effect of climate change on the biophysical and social systems are expected to vary significantly in different parts of India and will be determined by both global and local factors. To enable climate adaption and mitigation across the nation, thorough knowledge of climate systems, interdisciplinary approaches to simulate the trajectory of the complex systems, and sector-specific tools and services to enable climate resilience is the need of the hour.

In response to the serious threats posed by climate change to the development process and the limitations that India is facing, the Government of India as part of its comprehensive National Action Plan on Climate Change has a dedicated mission for development of appropriate institutional and human resource capacity for this purpose under the National Mission on Strategic Knowledge for Climate Change (NMSKCC), being coordinated by the Department of Science & Technology.

Under the Mission, DST is promoting interdisciplinary research by setting up Centres of Excellence (CoEs) and major R&D programme across the country in order to bring out the strategic knowledge of climate change in India and promote collaborative research across the nation. The rising number of citations and special mentions of Indian literature and in the Inter-governmental Panel on Climate Change (IPCC) assessment reports demonstrate evidence of the steadfast growth of climate science in India in the past decade.

Under the aegis of Ministry of Earth Sciences and Department of Science & Technology, a national team was set up under the Chairmanship of Dr. Akhilesh Gupta, Sr. Adviser DST. The team has now come up with a report entitled *"India's Climate Research Agenda: 2030 and Beyond"* which provides a detailed review and future research direction on various identified themes. I believe this report will provide guidance to India's climate community and the associated institutions to make meaningful contribution.

(S. Chandrasekhar)

Technology Bhavan, New Mehrauli Road, New Delhi - 110016
Tel: 0091 11 26511439 / 26510068 | Fax: 00 91 11 26863847 | e-mail: dstsec@nic.in | website: www.dst.gov.in

सत्यमेव जयते
डॉ. एम. रविचंद्रन
Dr. M. Ravichandran

सचिव
भारत सरकार
पृथ्वी विज्ञान मंत्रालय
पृथ्वी भवन, लोदी रोड, नई दिल्ली–110003

SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
PRITHVI BHAWAN, LODHI ROAD, NEW DELHI-110003

FOREWORD

Earth's climate changed gradually in the past century and rapidly over the last decade due to increased radiative forcing. The impacts of climate change are becoming increasingly evident through an increase in extreme weather events. These events lead to significant losses of lives and wasting away of important resources to impede the growth of rapidly improving infrastructure for Indian citizens. These events are likely to worsen unless we take appropriate steps.

The present report comprehensively outlines the key research areas that need to be addressed to mitigate the effects of climate change and adapt to changes that are already happening. These are in accordance with the principles and efforts of the Ministry of Earth Sciences (MoES) which has facilitated research in a wide spectrum of climate research including country-wide measurement networks and state-of-the-art climate modelling.

This report titled *"India's Climate Research Agenda: 2030 and Beyond"* provides a detailed review and future research direction in the following themes identified by experts - *Monsoon*, *Climate Modelling*, *Aerosol-Climate Interactions*, *Hydrology & Cryosphere*, *Extreme Events*, *Oceanic Sciences*, *Urban Climate*, *Carbon Cycle*, and *Sector-Specific Climate Services (Sectors:* Renewable Energy, Water, Disaster risk mitigation, Infrastructure Resilience, Agriculture, Coast, Health*)*. All chapters have been edited by Indian climate scientists and thoroughly reviewed. The present report will help to guide future ideas by researchers across the country to carry forward the vision of the MoES and other agencies; these are the need of the hour.

I wholeheartedly recommend this report titled "India's Climate Research Agenda: 2030 and Beyond" to anyone interested in learning more about climate change and the challenges it poses to India, and especially, to researchers across the country who wish to be a part of the scientific endeavour to mitigate and adapt to climate change.

(M.Ravichandran)

Tel. : +91-11-24629771, 24629772 ❑ Fax : +81-11-24629777 ❑ E-mail : secretary@moes.gov.in

विज्ञान और इंजीनियरी अनुसंधान बोर्ड
(विज्ञान और प्रौद्योगिकी विभाग, भारत सरकार का एक सांविधिक निकाय)
SCIENCE & ENGINEERING RESEARCH BOARD
(A Statutory body of Department of Science and Technology, Govt. of India)

डॉ. अखिलेश गुप्ता
सचिव
Dr. AKHILESH GUPTA
SECRETARY

PREFACE

India, like all other countries of the world, faces the challenge of dealing with the threat of climate change, while also trying to sustain rapid economic growth. Climate research across the world is focusing on developing resilience to address the impact of climate change, which in turn requires innovative approaches and interventions. Sustainable and regenerative development of ecosystems and communities warrant climate-compatible planning, implementation, and monitoring. The National Action Plan on Climate Change (NAPCC) released in June 2008 emphasised positioning dedicated research initiatives for developing long-term climate adaptation strategies to promote sustainable development and climate-resilient socioeconomic growth.

As one of the founding members of the Intergovernmental Panel on Climate Change (IPCC), India has contributed to global climate research since 1990 when the IPCC released its First Assessment Report (FAR). Following this several initiatives were undertaken by the government, including Monsoon Trough Boundary Layer Exp. (MONTBLEX) in 1990, India's Methane campaign in 1991, the Indian Climate Research Programme (ICRP) in 1997, the LAnd Surface Processes EXperiment (LASPEX) in 1997, Indian Ocean Experiment (INDOEX) in 1999, Bay of Bengal Monsoon Experiment (BOBMEX) in 1999, Arabian Sea Monsoon Experiment (ARMEX) in 2001, Experiment on Monsoon variability under TOGA-I in 2002, and the National Action Plan on Climate Change (NAPCC) in 2008. And in the following year in 2009, the NAPCC gave birth to eight National Missions on Climate Change anchored by seven central ministries and departments, Ministry of New and Renewable Energy (MNRE), Ministry of Power, Ministry of Urban Affairs, Ministry of Water Resources, Ministry of Agriculture & Cooperation, Ministry of Environment & Forests, and Department of Science & Technology (DST).

The DST is responsible for implementing two of these missions, the National Mission for Sustaining the Himalayan Ecosystem and the National Mission on Strategic Knowledge for Climate Change. With these efforts, it has, amongst other things, supported more than 200 projects, 15 centres of excellence, 30 major research and development programs, 14 network programs, six task forces, and 25 centres with over 1500 scientists and students working on these mission projects. In a similar vein, several research initiatives have been undertaken by the Ministry of Earth Science from the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology Pune. These include the development of the Earth System Model, IITM-ESM in partnership with the National Oceanic and Atmospheric Administration (NOAA), USA. CCCR also generates regional climate scenarios for monsoon in the Indian region through its participation in the World World Climate Research Programme (WCRP) initiative: COordinated Regional climate Downscaling Experiment (CORDEX), by dynamical downscaling of regional climate over large South Asian domain, using high resolution (50 km) Regional Climate Models (RCMs). These efforts have been crucial in understanding the weather and climate of the region and mitigating its effects.

3rd & 4th Floor, Block - II, Technology Bhawan, New Mehrauli Road, New Delhi - 110 016 INDIA | P: +91 11 26511125 F: +91 11 26511098 | E : secretary.serb@nic.in W : www.serb.gov.in, www.serbonline.in

विज्ञान और इंजीनियरी अनुसंधान बोर्ड
(विज्ञान और प्रौद्योगिकी विभाग, भारत सरकार का एक सांविधिक निकाय)
SCIENCE & ENGINEERING RESEARCH BOARD
(A Statutory body of Department of Science and Technology, Govt. of India)

डॉ. अखिलेश गुप्ता
सचिव
Dr. AKHILESH GUPTA
SECRETARY

The recently released sixth Assessment Report (AR6) of IPCC highlights the need for setting a new vision and agenda for climate research, to meet the challenges of the future impact of now "irreversible" climate change globally. Climate change is expected to increase extreme events like heat waves, cyclones, heavy rainfall, floods and droughts. These will likely affect India directly or indirectly by accentuating increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems. Thus, underscoring the urgency for climate research that would help India mitigate extreme events and increase climate resilience. Hence, we believe in the need for a long-term vision for climate research in the country to identify key priority areas of climate research. The DST through its deep consultations with experts in the country have identified the following six broad priority areas for climate research in the country for 2030: climate modelling, extreme events, glaciology, urban climate, aerosols, and Himalayan ecosystem studies.

A detailed climate research agenda and vision report for 2030, titled "*India's Climate Research Agenda: 2030 and Beyond*" has been developed by a national drafting committee. Each chapter in this report is based on the identified themes in Climate Science and Adaptation - *Monsoon*, *Climate Modelling*, *Aerosol-Climate Interactions*, *Hydrology & Cryosphere*, *Extreme Events*, *Oceanic Sciences*, *Urban Climate*, *Carbon Cycle* and *Sector-specific Climate Services*. The nine themes each have a group of lead authors and reviewers who have presented a comprehensive evaluation of climate research carried out by the Indian scientific community, gaps in climate research, and futuristic avenues to bridge these gaps. The chapters were written, thoroughly expert-reviewed, and finalized over the last 8 months. This report will prove to be hugely beneficial for scientists, policymakers, and even students. I wholeheartedly thank the contributors who made this report, *"India's Climate Research Agenda: 2030 and Beyond"*, possible.

New Delhi, India
22nd May 2023

Dr. Akhilesh Gupta
Secretary, Science and Engineering Research Board
Senior Adviser, Department of Science and Technology
Ministry of Science and Technology
Government of India

3rd & 4th Floor, Block - II, Technology Bhawan, New Mehrauli Road, New Delhi - 110 016 INDIA | P: +91 11 26511125 | F: +91 11 26511098 | E : secretary.serb@nic.in | W : www.serb.gov.in, www.serbonline.in

भारतीय प्रौद्योगिकी संस्थान मुंबई
पवई, मुंबई- 400 076, भारत
Indian Institute of Technology Bombay
Powai, Mumbai-400 076, India
Phone : (+91-22) 2572 2545
Website : www.iitb.ac.in

ACKNOWLEDGEMENTS

Unprecedented and intensified Climate change is affecting every aspect of life around the globe. IPCC 6th Assessment Report highlights the urgency of Climate Adaptation and Mitigation to reduce the risk to humanity due to the Climate Change threat. India is experiencing a rapid growth and development, to make our development climate-aware and climate-resilient, we need to outline our vision and agenda for climate research. This is what has motivated the Department of Science and Technology (DST) to bring India's climate experts to collaborate and identify key priority areas of climate research, and set up a National Drafting Committee to prepare a detailed Climate Research Agenda and Vision for 2030 and beyond. The report titled *"India Climate Research Agenda: 2030 and Beyond",* which provides a detailed climate research agenda for the country, is the culmination of recently reviewed scientific advancements in climate science and adaptation with identified knowledge gaps. The report expounds on the future research direction in the identified themes on *Monsoon, Climate Modelling, Oceanic Sciences, Aerosol-Climate Interactions, Extreme Events, Urban Climate, Hydrology & Cryosphere, Carbon Cycle,* and *Sector-Specific Climate Services*.

I offer my sincere gratitude to Dr. Akhilesh Gupta, Secretary, Science and Engineering Research Board, Department of Science and Technology. This report is his brainchild, and he has continuously and wholeheartedly guided, encouraged, and supported us in every research endeavour. Our heartfelt thanks to Honourable Union Minister of the Ministry of Science and Technology, Dr. Jitendra Singh, who has honoured us by writing the *Message*, Honourable Secretary to the Department of Science and Technology, Dr Srivari Chandrasekhar and the Honourable Secretary to the Ministry of Earth Sciences, Dr M Ravichandran for being kind enough to provide a *Foreward* to this report.

We sincerely acknowledge and applaud the lead authors of the nine climate themes respectively, Prof. Arindam Chakraborty (IISc Bangalore), Prof. Pankaj Kumar (IISER Bhopal), Dr. Srinivasa Kumar Tummala (INCOIS Hyderabad), Prof. V Vinoj (IIT Bhubaneshwar), Prof. Sandeep Pattnaik (IIT Bhubaneshwar), Prof. Rajesh Kumar Mall (Banaras Hindu University), Prof. Vimal Mishra (IIT Gandhinagar), Prof. Manish Kumar Goyal (IIT Indore), Dr. H S Hosalikar (India Meteorological Department Pune), who have enthusiastically coordinated with the following scientists to bring forth this report, Prof. Suneet Dwivedi (University of Allahabad), Dr. A K Sahai (IITM Pune), Dr. V S Prasad (NCMRWF Noida), Dr. R Krishnan (IITM Pune), Prof. Saroj Kanta Mishra (IIT Delhi), Prof. S A Sannasiraj (IIT Madras), Prof. Sagnik Dey (IIT Delhi), Dr. M. V. Ramana Murthy (National Centre for Coastal Research), Prof. Dr. V. Geethalakshmi (TNAU), Prof. Udit Bhatia (IIT Gandhinagar), Prof. Ashwin

Seshadri (IISc Bangalore), Dr. Rajesh Kumar (Central University of Rajasthan), Prof. Anil Kumar Gupta (National Institute of Disaster Management), and Prof. Subhankar Karmakar (IIT Bombay). Our thanks would be incomplete without acknowledging the expert reviewers of this report - Prof. S K Dash (IIT Delhi), Dr. R Krishnan (IITM Pune), Prof. U C Mohanty (IIT Bhubaneshwar), Prof. Gufran Beig (NIAS), Prof. B S Murty (IIT Madras), Prof. Anil V Kulkarni (IISc Bangalore), Prof. Ashok Karumuri (University of Hyderabad), Prof. Dev Niyogi (University of Texas), Prof. P P Mujumdar (IISc Bangalore), Dr. Chandra Shekhar Jha (NRSC), Prof. N H Ravindranath (IISc Bangalore), Prof. P Vinaychandran (IISc Bangalore), Prof. Raghu Murtugudde (University of Maryland, now at IIT Bombay), Dr K J Ramesh (IMD), Dr. Shailesh Nayak (NIAS), Dr. A K Sahai (IITM Pune), Dr. Ajit Tyagi (South Asian Meteorological Association).

I sincerely acknowledge the hard work and efforts made by Ms. Sheeba Sekharan in compiling the report. I thank Tejasvi Chauhan, Nivedita Dubey, Leena Khadke, Dr. Taveen Singh Kapoor and Priyam Prasambit Tripathy for their significant contributions to the report. I acknowledge Tannu Kaushik, Priyam Prasambit Tripathy, Pooja Manwani, and Puja Tripathy for designing the cover page of the report. I also thank Dr. Nisha Mendiratta and Dr. Susheela Negi for their continuous support during the preparation of the report.

A two-day International Climate Research Conclave (ICRC-2023) is being hosted at IIT Bombay on 26-27 May 2023, sponsored by MoES and DST, to discuss India’s recent progress in climate research and develop a long-term research agenda and vision for 2030 and beyond, with invited participation of around 200 climate scientists, students, experts, policy makers, and retired meteorologists. We cannot thank enough the whole committee of showrunners who have been burning the midnight oil to successfully make the ICRC-2023 happen (complete list at end of the report).

May, 2023
Mumbai, India

SUBIMAL GHOSH
Interdisciplinary Program in Climate Studies, IIT Bombay

Contents

EXECUTIVE SUMMARY

The Intergovernmental Panel on Climate Change (IPCC), Assessment Report 6 (AR6), stated that the recent climate change is “widespread, rapid, intensifying and unprecedented in thousands of years.” It is further noted: “Climate change is already affecting every region on Earth in multiple ways. The changes we experience will increase with further warming.” Managing the unavoidable climate change, known as Climate Adaptation, involves a sound understanding of climate processes and modeling, model and process uncertainties, the sectoral needs, and merging into sector-specific climate service tools (Figure 1). Considering the climate urgency in India, from an adaptation perspective, it is crucial to review the existing scientific and technological development in Climate Science and Adaptation and identify the country’s future research direction. The present report identifies the following themes for the detailed review, 1. *Monsoon*, 2. *Climate Modeling*, 3. *Oceanic Sciences*, 4. *Aerosols*, 5. *Extreme events*, 6. *Urban Climate*, 7. *Hydrology & Cryosphere*, 8. *Carbon cycle* and 9. *Sector-specific Climate Services*. The summary of the review is presented here.

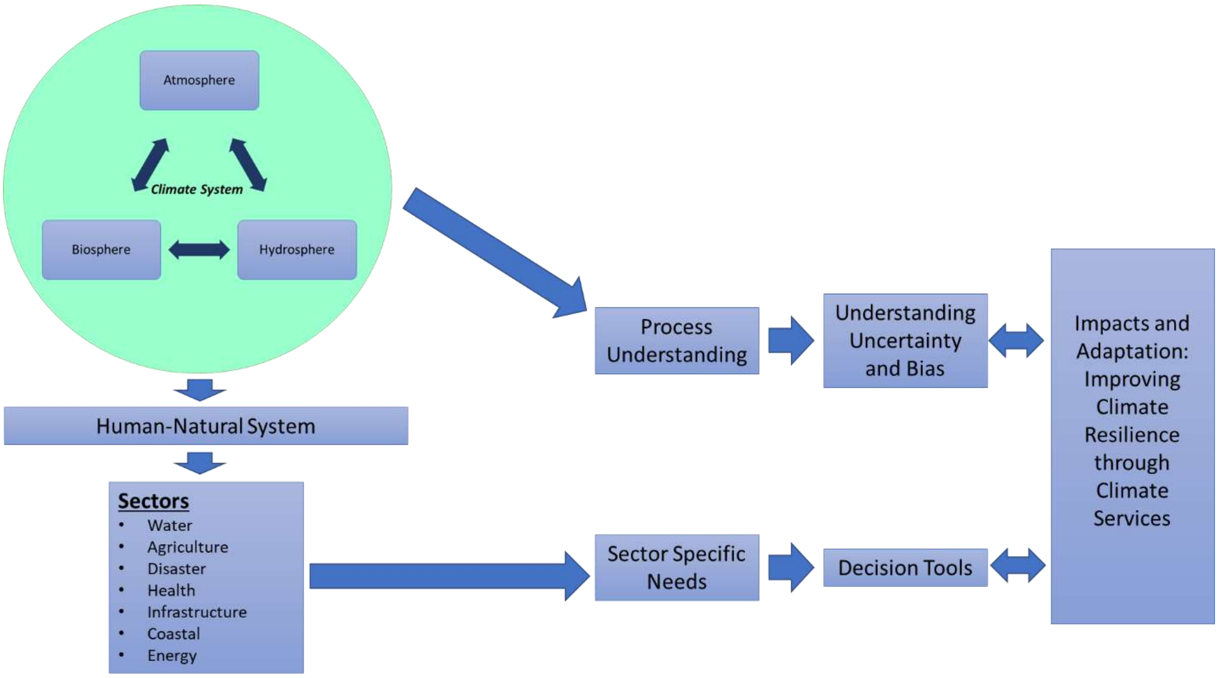


Figure 1: Interdisciplinary Research in Climate Science and Climate Adaptation

MONSOON

The Indian subcontinent receives around 80% of its annual rainfall during the summer monsoon, from June to September. Hence, variability in summer monsoon rainfall has significant implications for agriculture, water resources management, and the country's economy. In addition to year-to-year variation, the ISMR exhibits substantial multidecadal and millennial-scale variations in rainfall. In recent decades, India has observed an increasing trend in precipitation extremes and heat waves attributed to global warming. Hence, an accurate ISMR prediction needs a clear understanding of monsoon and its associated processes at varying time scales, considering both thermodynamic factors and dynamics, including feedback processes. Although our understanding of the monsoon has improved in recent decades, there are still many unanswered questions ranging from the multiscale nature of monsoon precipitation to global teleconnections of monsoon to the role of land-surface processes during monsoon. To efficiently address these research gaps and to better predict monsoon rainfall, this report outlines a comprehensive and ambitious plan for advancing Indian summer monsoon research and prediction with specific short-term and long-term goals.

Short-term goals to address these gaps by 2030 stress on the need for interdisciplinary collaboration between researchers working on various facets of monsoon and the industry to translate the existing knowledge into useful products for end users, such as farmers. Free availability of model simulations and observed data and the development of a network of RADAR and AWS across the country will help accelerate climate services and research on the dynamics of ISMR. The long-term goals beyond 2030 highlight the need to develop state-of-the-art Earth System Models, including the vegetation dynamics and irrigation practices specific to India. These goals also underscore the need to understand the linkage between different components of monsoon from cloud scale to large-scale teleconnection, including region-specific interactions between land and atmosphere.

CLIMATE MODELING

Intergovernmental Panel on Climate Change (IPCC) Assessment Reports highlight that anthropogenic warming affects each component of the earth’s system based on the simulations of Global climate models (GCMs). However, studies have reported that GCMs cannot accurately reproduce India's typical monsoon climate because of their limitation in simulating many aspects of monsoon dynamics. Hence, there is a need for regional customization of GCM, a high-resolution Regional Earth System Model (RESM). Running RESMs for all climate change scenarios for several hundred-year time scales is computationally expensive. Machine Learning (AIML) and Deep Learning (DL) techniques also offer an excellent parallel approach to overcome these limitations. Such regional earth System models should be developed by India, including regional aspects of the Indian monsoon, accurate representation of clouds, convection processes, and cloud and land surface heterogeneity. The land surface component of the model should also include dynamic agriculture, irrigation processes, vegetation, and soil properties for better projection of future impact assessment studies.

The short-term roadmap for India’s climate models development plan includes 1) setting up a national body of climate modelers (NCBM) involving researchers and academicians from diverse fields, 2) Identifying a few better-performing state-of-the-art coupled ocean-land-atmosphere models to understand the processes and limitations. 3) Improvisation of limitations of models, such as cloud, convection, and land-surface parameterization. 4) development of hybrid modelling (AIML + climate models) for district-level vulnerability-risk assessment and mitigation strategies. 5) Training and human resource generation by organizing workshops on climate modelling. The long-term strategies require a thrust to research paleoclimate to understand the past better and the development of finer resolution GCM. Setting up the publicly available robust community models, allowing the decoupling of different components, and simplifying the complex climate system for a better understanding of drivers. A research-application feedback system can be set to meet necessary requirements of forecasting and climate extreme prediction systems by integrating AI/ML with climate modelling. This could include suggesting/planning new observations/field campaigns based on requirements.

OCEANIC SCIENCES

Global warming is leading to the melting of ice in the polar regions and internal expansion of oceans, which results in sea level rise and an increase in the frequency and intensity of extreme events such as marine heatwaves, droughts, forest fires, and higher rates of erosion affecting beaches, deltas, and islands, etc. The tropical Indian Ocean has experienced basin-wide warming with an average estimated rise of about 1℃ relative to 1951, at a rate of 0.15℃ per decade. The Arabian Sea witnessed a maximum increase in heatwave events at a rate of ~1.5 - 2 events/decade. In addition to anthropogenic changes, natural climate variabilities such as coupled dynamics of the Indo-Pacific warm pool, El Niño Southern Oscillation (ENSO), and the Indian Ocean Dipole (IOD) contribute to intensifying the extreme events in interannual and decadal timescale. Hence, there is a need to study the changes in the regional physical and ecological properties of the Indian Ocean region to increase our resilience against climate change and facilitate robust and climate-ready policymaking for adapting and mitigating climate risk.

Although our understanding of the coupled ocean and atmospheric processes has improved significantly in recent decades, the changing biogeochemistry and ecological response to climate change in the Indian Ocean is relatively unexplored. In addition, models also struggle to realistically simulate changes in the coastal circulations and uncertainty in the ice loss in the glaciers and ice sheets. In the short term, we need to employ an integrated approach to study the combined impact of land-surface processes, coastal and open ocean processes, and ice sheets/glaciers to improve our understanding of extreme events and sea level rise. There is an urgent need to enhance the high-resolution model development and data assimilation techniques, modelling ecosystems and higher trophic levels, and observations. Our long-term goals should be to provide assessments of coastal erosion and flooding, protection of mangroves, maintain food security, sanitation of drinking water, and disease control in the event of extreme sea level rise under the global climate change scenario.

AEROSOL-CLIMATE INTERACTIONS

Atmospheric aerosols, arising from natural and human activities, impact the Earth's radiation budget through scattering, absorption, and cloud interactions. They rank second in radiative forcing but face significant uncertainties due to inter-model differences originating from an inadequate understanding of their properties. India presents a unique case with diverse aerosol sources activated across various scales, influenced by natural phenomena. The dynamic nature of aerosols, coupled with India's diverse land use, leads to complex interactions with radiation, clouds, precipitation, and climate. This chapter offers guidance for aerosol research in India to mitigate their effects and enhance resilience.

Efforts are needed to expand and strengthen the ground-based observational network for aerosols and related climate variables. This entails adding more sites and advanced instrumentation to monitor evolving aerosol species, including biological aerosols, absorption, and chemical composition. It is also crucial to enhance the capability for satellite retrieval of aerosol properties over land, utilizing Indian satellites and developing ground-based, airborne, and space-borne instrumentation, thereby advancing the technological ecosystem. Additionally, campaign mode research activities should be expanded, focusing on understanding aerosol impacts on mixed-phase clouds. These may further help to improve understanding of their impact on snow darkening and mixed-phase clouds. These will help to pursue longer-term goals of cultivating expertise in incorporating interactive aerosol modules within regional and global climate models. Additionally, the development of updatable high-resolution emission inventories should be prioritized. Long-term observations, along with the integration of interactive aerosols in Indian climate models, are crucial. Standardized measurement technologies play a vital role in achieving these objectives. Moreover, understanding the impact of aerosols on monsoons and tropical cyclones is necessary for formulating effective future policies.

EXTREME EVENTS

Over the past decades, India has experienced a range of extreme weather events, such as floods, droughts, tropical cyclones, heat waves, cold waves, etc. In 2022, India witnessed more than 241 extreme weather events, killing over a thousand people across central, eastern, and north-eastern regions. Odisha, Andhra Pradesh, Assam, Bihar, Kerala, and Maharashtra were found to be the most vulnerable states to weather extremes. Recent research reveals that floods contribute to 46.1% of the mortality rate from extreme weather events, followed by tropical cyclones at 28.6%. Effective disaster preparedness has reduced tropical cyclone deaths by 94% in past decades, but heat waves and lightning have seen mortality increases of 62.2% and 52.8%, respectively. Additionally, recurring weather extremes between 2006-2021 have caused crop loss of 36 million hectares, leading to a loss of 3.75 billion USD to farmers. Increased intensity and frequency of extreme events highlight the need for immediate and sustainable climate actions.

In the short term, there is a need to focus on six key areas, which include the development of high-density observation networks, improved regional modelling approaches to develop early warning systems, and bringing scientific understanding to policymakers for preparing resilience and adaptive measures. The long-term goal should be to generate a sustainable and robust risk assessment and management framework, improve urban planning, understand key indicators triggering location-specific extreme weather events, restore coastal wetlands, promote environmental awareness campaigns, and develop comprehensive region-specific adaptation strategies. In conclusion, increasing resilience against extreme events requires a multifaceted approach, which includes reforming infrastructure, identifying potential risks, introducing proactive strategies, and increasing awareness to fortify vulnerable communities.

URBAN CLIMATE

Climate change's impact on cities is evident in basic services, infrastructure, housing, livelihoods, and public health. With 68% of the global population projected to live in urban areas by 2050, the UN warns of increased health and economic losses due to climate events, necessitating action on construction and transportation. India holds the world’s second-largest urban system, accommodating nearly 11% of the world's urban population. Urban India witnesses evidence of climate change, including rising temperatures, sea-level rise, air pollution, extreme events like floods, droughts, heat waves, urbanization, increased infrastructure, and ecological imbalances. This chapter focuses on solving the key issues faced in urban India because of the changing climate, possible problems that may arise in the future, and what the climate research community needs to focus on in the long and short terms. The short-term goals include building climate resilient infrastructure and resource efficiency; improving early warning systems and forecasting; improvement in climate model simulations; high-resolution city-specific inventory; modelling urban heat islands; advancing research in public health modelling; urban flood modelling and mapping; and adapting strategies to mitigate climate change impacts. And in the longer-term, further research focus is suggested on making cities carbon-neutral; advancing research in early warning systems; micro-scale modelling; emission inventory for criteria air pollutants; the impact of long-term exposure to pollution and extreme temperature; sustainable cooking energy; socio-economic impacts of climate change on cities; disaster risk reduction; ease of access to urban climate data; and changing urban water cycles. These will help to make our cities more resilient and especially help the poor and marginalized residents that face the brunt of the stresses and burdens. Ultimately, upgrading and adopting climate-adapted research-driven policies and planning of land use and urban development will potentially reduce damages caused by the changing climate.

HYDROLOGY & CRYOSPHERE

The water cycle is a complex system influenced by natural and anthropogenic changes. As the Earth's atmosphere warms due to global warming, it can hold more water vapor leading to increased extreme events, such as floods and droughts. Human activities, such as deforestation and urbanization, can alter water storage in the soil, vegetation, and groundwater. The frozen water on earth, collectively called ‘the cryosphere,’ is also changing due to global warming. Projected increases in temperature threaten an increase in the glacial melt, ultimately reducing the amount of water available for drinking, irrigation, and hydropower generation and an increased risk of glacial lake outbursts and floods. The Indian summer monsoon rainfall (ISMR) has declined in recent decades, with the most significant decreases in the Indo-Gangetic Plain, the northeast region, and the Western Ghats. The decline in rainfall also leads to an increase in the frequency and intensity of droughts, which can have a devastating impact on agriculture, livelihoods, and the socio-economy of India.

There is a clear uncertainty about future water availability, primarily limited by our lack of understanding of the cryosphere, precipitation, groundwater, and dynamics of extremes like floods and droughts. The short-term goals, hence, should target increased observations of glaciers across the Himalayas, constrain the uncertainties in hydrological and climate models and promote early warning systems with reasonable indices of extremes for planning and water resources management. Long-term goals should be to generate high-quality observation data of precipitation/snow across India, including the Himalayas, to improve the streamflow and precipitation predictions in high altitudes, create a country-wide carbon flux and greenhouse gasses observation network at urban and ecological hotspots, and promote flood and drought preparedness at the community level. There is also a need to develop a framework to capture drought propagation mechanisms under coupled human-water interactions.

CARBON CYCLE

The atmospheric CO_2 content has risen sharply due to the accelerated rates of anthropogenic emissions to levels unprecedented in the last three million years. The carbon cycle - the key to the functioning of life-supporting systems - through its natural sinks, absorbs a smaller proportion of these emissions and has significantly disrupted the fragile balance much beyond the normal oscillations. Therefore, a deeper understanding of the functions of the carbon cycle is to understand the trajectories of the future. The "India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change" provides an overview of India's efforts to address climate change. India's targets are to reduce the emissions intensity of GDP by 33-35% by 2030, increase the share of non-fossil fuels in its energy mix to 40% by 2030, and create an additional carbon sink of 2.5-3 billion tonnes of CO_2 through additional forest and tree cover by 2030. To achieve these targets, research and development in the field of carbon cycle modelling and carbon budget assessment is necessary. The quantification of shifts in the present carbon cycle is required to develop a better ability to predict its future evolution.

Creating national-level vegetation productivity data considering the CO_2 fertilization effect and the role of meteorological drivers and estimation and projection of the carbon uptake potential of Indian forests and intensified agriculture will help plan to achieve the net zero emission target. The short-term goal for India must be to maintain the carbon budget plan for each decade by encouraging research and development and investment in climate solutions, including carbon sequestration techniques, and it should expand by 2030. In the long term, the development of models, quantifiable scientific data, and robust observations are needed to establish the emissions and understanding of CO, CO_2, and CH_4, changes in carbon stocks, and the factors controlling these activities. Finer spatial and temporal resolution remote sensing data from satellites should be made accessible to researchers, which can be used for vegetation model training and validation.

AGRICULTURE

Climate services for agriculture provide appropriate climate information, impact-based forecasts, and weather-informed agricultural advisories to mitigate extreme weather, leading to social, environmental, and economic benefits. It helps in capacity building for last-mile communication, user-driven and participatory tailoring of services, and translation of relevant services into actionable products. The roadmap for agriculture climate services should consist of expanding the current knowledge of agricultural systems by increasing field data collection, installing more automatic weather stations, and developing a common database that is accessible to all researchers and stakeholders. Improving the weather forecast and prediction that must be translated to stakeholders in a simple and understandable way. In long-term plan may include developing the climate and crops model for a better understanding of climate and vegetation interaction.

WATER

India is under significant water stress, which affects both water and food demand. India is taking significant steps in water management practices through irrigation, integrated water management systems, research, and innovation of new water-saving techniques. The 2030 plan aims to provide India-specific modelling through the integration of land surface models by including glacier components, Indian region-specific water management, and crop practices, and coupling groundwater with lateral flows. Further, long-term planning involves achieving clean water and sanitation sustainable development goals by a multi-faceted, sustained approach that addresses the issues of infrastructure, policy, education, and technology. It requires coordinated efforts from various stakeholders, including government agencies, NGOs, the private sector, and local communities.

DISASTER RISK MITIGATION

Climate change has led to an increased frequency and magnitude of extreme hydro-climatic events, such as floods, droughts, and heat waves, causing disastrous impacts on societies and ecosystems worldwide. With its unique geo-climatic and socio-economic conditions, India is particularly vulnerable to a wide range of disasters with eight out of 36 states in India experiencing more than 50 disasters during 1995-2020. Disaster risk mitigation and preparedness need to involve multidisciplinary efforts, integrated policy planning and decision-making, improved forecasting and preparedness, and providing adaptation support. This will require a focus on establishing a public hydro-climatic database, improving forecasting and early warning systems, establishing multi-purpose shelters, conducting risk and vulnerability assessments, and integrating adaptation and resilience strategies. These facilitate the long-term goals of proper disaster knowledge management in a multi-stakeholder approach, nature-based solutions, comprehensive risk reduction, resilience, strategies, and capacities.

INFRASTRUCTURE RESILIENCE

India is particularly vulnerable to threats that target critical infrastructure systems. These threats include intensifying weather extremes, technological failures, or a combination of both, which are likely to become more frequent and severe in the future due to global changes. Hence, traditional risk-based approaches that focus on strengthening individual components to withstand threats may no longer be sufficient. In the short term, there is an urgent need to identify and recognize physical infrastructure as 'critical infrastructure systems' and generate recovery intervention strategies for each system. In the long term, the goal should be to generate a theoretical framework to quantify the resilience of all interdependent frameworks in the context of evolving hazards like climate change.

HEALTH

Climate change impacts human health globally, and interdisciplinary research on climate change and human health is needed to reduce the public health burden and generate strategic knowledge. The current knowledge gaps include the lack of a systematic approach to translating knowledge into action, inadequate expertise for translational research, limited indigenous health-risk assessment, and the absence of a consolidated data management system. Noting the above, it has been suggested to develop customized climate products for health applications, enhance disease management systems, create indigenous exposure-response functions, build analytical tools for data, and develop decision support systems in the short term. Whereas, the suggested long-term roadmap includes an inclusive curriculum, interdisciplinary research ecosystem, and systematic cohort planning.

COAST

The coastal economy sustains over 4 million fishermen and coastal communities, and thus it is essential to monitor, understand, and predict the dynamics of the Indian Ocean. The focused approaches to achieve the national goals by 2030 includes, (1) establishing the ocean and coastal climate mission at the national, state, and district/regional level, (2) periodically preparing the coral eco-morphological maps for protecting the coral ecosystem from coral acidification, (3) a reliable and timely advisory on the potential zones of fish aggregation, (4) hybrid management system for handling the river sediment, (5) a framework for the coastal districts and Islands in case of any extreme or hazardous event, (6) disaster mitigation practice to develop resilient cities. These approaches aim to enhance coastal life through skill building, training, upgrading traditional technologies, and time-bound action plans.

RENEWABLE ENERGY

India has set an ambitious decarbonization goal for its energy sector, in which wind and solar energy are projected to be the largest sources of renewable growth. Therefore, climate science plays an important role in the energy transition of India. On a shorter timescale, expansion of electricity generation from renewables, resource assessment, grid integration, and their uncertainty quantification, are required. In the long term, there is a need to develop climate models at higher resolutions to generate better estimates of wind and solar energy availability. Given the importance of synoptic and mesoscale variability for various aspects of renewable energy generation, numerical weather prediction and coupled climate models will grow in importance for India's energy sector.

BACKGROUND

India is faced with the challenges of sustaining rapid economic growth while dealing with global threat of climate change. The research across the world is focusing on developing climate resilience to address impact of climate change. This would require innovative approaches and interventions. Sustainable and regenerative development of the ecosystems and communities can only be through climate compatible planning, implementation and monitoring. The National Action Plan on Climate Change (NAPCC) released in June 2008 had emphasised on positioning dedicated research initiatives for developing long- term adaptation strategies to promote sustainable development and climate resilient socio-economic growth.

India's efforts in Climate Research

India has been one the founder countries for establishing the Inter-governmental Panel on Climate Change (IPCC) and had taken lead in climate research right from the time IPCC released its First Assessment Report (FAR) in 1990. Monsoon Trough Boundary Layer Exp. (MONTBLEX)- 1990 and India's Methane campaign,1991 were the two initiatives taken by India after FAR release. After the release of Second Assessment report (SAR) in 1996, Department of Science & Technology, Government of India launched an ambitious programme, Indian Climate Research Programme (ICRP) in the year 1997. Around the same time three major field experiments viz., LAnd Surface Processes EXperiment (LASPEX) – 1997; Indian Ocean Experiment (INDOEX),1999 and Bay of Bengal Monsoon Experiment (BOBMEX)-1999 were initiated. Two more field experiments viz., Arabian Sea Monsoon Experiment (ARMEX),2001 and Experiment on Monsoon variability under TOGA-I, 2002 were also launched around the time when Third Assessment Report (TAR) was released in 2001. India initiated setting up of an International Centre for Climate Change Research in 2002. However, some major initiatives came up only after IPCC released its Fourth Assessment Report (AR4) in 2007 followed by which India launched its National Action Plan on Climate Change (NAPCC) in 2008. As part of NAPCC 8 National Missions on Climate Change were initiated in 2009 anchored at 7 central ministries/departments viz., Ministry of New and Renewable Energy (MNRE), Ministry of Power, Ministry of Urban Affairs, Ministry of Water Resources, Ministry of Agriculture & Cooperation, Ministry of Environment & Forests and Department of Science & Technology (DST). DST was entrusted with the implementation of two national missions.

Initiatives under NAPCC

DST is implementing two national missions on climate change as part of the National Action Plan on Climate Change. These are (a) National Mission for Sustaining the Himalayan Ecosystem and (b) National Mission on Strategic Knowledge for Climate Change. These missions have done considerably well. DST have supported more than 200 projects like, 15 Centres of Excellence, 30 Major R&D programs, 14 Network programs which comprises of nearly 100 projects, 6 Task Forces; 25 State CC Centres, etc. During the last 8 years, as many as 2000 research papers in high impact factor journals were published. More than 100 new techniques have been developed and nearly 50,000 people are trained, 1.5 lakh given exposure as part of these missions. More than 1500 scientists and students are working on these mission projects.

Similarly, as part of Centre for Climate Change Research (CCCR), as part of IITM Pune a number of research initiatives have been initiated. CCCR developed an Earth System Model, IITM-ESM in partnership with National Oceanic and Atmospheric Administration (NOAA), USA, CCCR is also generating regional climate change scenarios for Indian monsoon region by participating in the World Climate Research Programme (WCRP) initiative: COordinated Regional climate Downscaling Experiment (CORDEX), by dynamical downscaling of regional climate over the large domain covering South Asia using high resolution (50 km) Regional Climate Models (RCMs).

Recent IPCC Reports and implication for India

IPCC brought out its 6th Assessment Report (AR6). Projected climate change as brought out by the Working Group-I (WG-I) report released last year, provided the starkest warning yet about the deepening climate emergency, with some of the changes already set in motion thought to be "irreversible" for centuries to come.

Here is a summary from WG-I report and its consequences for India-

- Averaged over the next 20 years, global temperature is expected to reach or exceed 1.5 degrees Celsius of warming. Limiting global warming to close to 1.5 degrees Celsius or even 2 degrees Celsius above pre-industrial levels "will be beyond reach" in the next two decades without immediate, rapid and large-scale reductions in greenhouse gas emissions. The 1.5 degrees Celsius threshold is a crucial global target because beyond this level, so- called tipping points become more likely.
- At 2 degrees Celsius of global warming, heat extremes would often reach critical tolerance thresholds for agriculture and health.
- The changes include more intense rainfall and associated flooding, more intense drought in many regions, coastal areas to see continued sea level rise throughout the 21st century, the amplification of permafrost thawing, ocean acidification, among many others.
- The projected changes in climate will have serious consequences for India in terms of increase in extreme events like heat waves, cyclones, heavy rainfall, sea level rise, floods and droughts. The country is likely to face a dichotomy of leading a proactive climate action which corresponds to less than 2 degree C rise by end of century, yet getting impacted severely due to large population density and poverty and some of its region and population having weak capacity to adapt to changing climate. CC would impose some major challenges on food, water, energy and health security.

IPCC Working Group 2 (WG-II) report recognizes the interdependence of climate, ecosystems and biodiversity and human societies and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non- climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic. The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in the WGII report. Across all three AR6 working groups, risk provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related hazards, the exposure and vulnerability of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept.

DST carried out all India district wise vulnerability assessments using a common framework (AR5 new definition). A summary of the outcome of this exercise is:

- 8 States which are highly vulnerable include Jharkhand, Mizoram, Orissa, Chhattisgarh, Assam, Bihar, Arunachal Pradesh, and West Bengal, all in the eastern part of the country, requiring prioritisation of adaptation interventions and upscaling their adoptive capacity.
- Among the top 100 most vulnerable districts in the country, more than 70% of them are in 5 States viz., Assam (24 district), Bihar (23 districts), Jharkhand (11 districts), Uttar Pradesh (8 districts), Odisha (7 districts)
- 60-90% of districts in three States viz., Assam, Bihar, Jharkhand have high Vulnerability

Major Climate Research Challenges for 2030

The 6th Assessment report of IPCC clearly brings out the need for setting a new vision and agenda for climate research in India to meet the challenges of future impact of climate change in the country. It is the research that would help India becoming climate resilient and mitigating extreme events. We need to work on a long-term vision for climate research in the country and identify key priority areas of climate research. DST through its deeper consultations with experts in the country identified following 6 broad priority areas for climate research in the country for 2030:

- Climate Modeling
- Extreme events
- Glaciology
- Urban climate
- Aerosols
- Himalayan Ecosystem studies

It is proposed to set up a National drafting Committee to prepare a detailed Climate Research agenda and vision for 2030. The present report serves the same purpose.

International Climate Research Conclave (ICRC-2023) at IIT Bombay

To discuss India’s recent progress in climate research and its agenda and vision for 2030, it was proposed to organize a two-day International Climate Research Conclave (ICRC-2023) at DST’s Excellence in Climate Change at IIT Bombay on 26-27 May 2023. In the conclave the scientists from different parts of India will discuss on the draft and prepare the roadmap for the country’s Climate research development.

CHAPTER 1: MONSOON

Arindam Chakraborty, Suneet Dwivedi, A K Sahai

Coordinating Lead Author
Prof. Arindam Chakraborty, IISc Bangalore

Lead Authors
Prof. Suneet Dwivedi, University of Allahabad
Dr. A K Sahai, Indian Institute of Tropical Meteorology, Pune

BACKGROUND

The word *Monsoon*, generally synonymous with the phrase *Summer Monsoon*, brings different perspectives to different sections of society. While for the commons, *Monsoon* is a relief from the scorching heat of the summer, for more intriguing observers and poets, it is an orchestration of fascinating phenomena from tall-dark clouds to torrential rain with gusts that has never failed to happen during the past millenniums. While for the agriculture sector, *Monsoon* is a necessity intertwined with livelihood, for water resources, it is at the center of policy making. Finally, for the forecasters, *Monsoon* is a milestone toward which a long way has already been covered but an even longer path yet to be travelled.

The reason behind such grave importance of the Monsoon lies in the fact that the Indian subcontinent receives about eighty per cent of the annual total rainfall during summer (June to September). Such strong seasonality of the Indian summer monsoon (ISM) can be attributed to seasonal interhemispheric migration of the Inter-Tropical Convergence Zone (ITCZ) --- a zonally elongated region of precipitation maxima and energy flux divergence (Figure 1.1) (Donohoe et al., 2013; Kang et al., 2008). ISM is a part of such a large-scale organization of clouds and moist convection.

The zonally averaged meridional circulation in the tropics is dominated by the cross-equatorial Hadley cell, the ascending branch of which resides over a region of deep convective clouds, forming the ITCZ (Adam et al., 2016). The zonal mean location of ITCZ in the differentially warmer hemisphere is anti-correlated with the interhemispheric energy transport at the equator. Although these systems have been studied as part of the zonal mean meridional overturning circulation using the energy budget framework, considerable challenges exist when the zonal asymmetries are considered (Biasutti et al., 2018). These heterogeneities arising out of land-sea boundaries, land surface variabilities, aerosol concentrations, the influence of orography, and associated energy distribution define the intricate characteristics of regional monsoon systems.

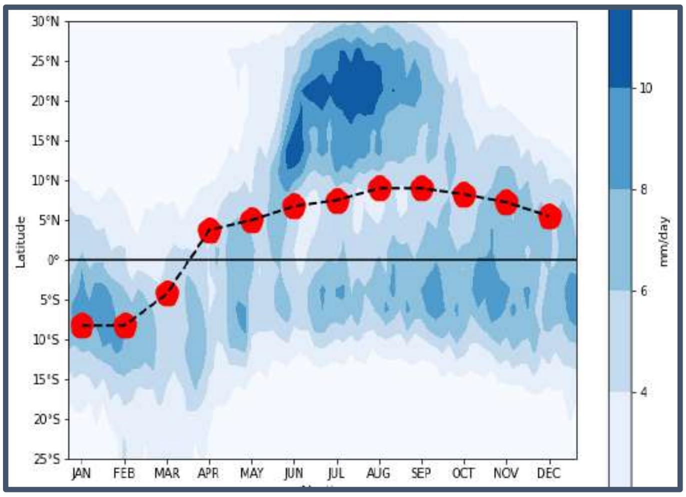


Figure 1.1: Seasonal cycle of the location of the maxima in zonal mean vertically integrated moisture convergence (red disks) and precipitation averaged over 70-90E (shaded). The vertically integrated moisture convergence is given by precipitation minus evaporation (P-E). This figure suggests the need to understand covariations of land ITCZ (primarily covered in 70-90E) and oceanic ITCZ (mostly covered in zonal mean). Units are in mm/day.

Besides this mean picture, Indian summer monsoon rainfall (ISMR) exhibits substantial variations at interannual to multidecadal to millennium time scales (Gadgil, 2003; Goswami, 2006; Sinha et al., 2015). The one standard deviation of the interannual variations of ISMR is about ten per cent of its long-term mean, which is about 880 mm. However, the interannual variability varies substantially with decades bringing multidecadal variations in drought and flood frequency (Karmakar et al., 2020; Preethi et al., 2019).

Indian monsoon also experiences substantial variations in precipitation intensity at sub-seasonal time scales. This monsoon intraseasonal oscillation (MISO) is one of the most widely studied topics regarding the Indian summer monsoon. MISOs are often connected to the northward propagation of convective cloud bands from the equatorial Indian Ocean (Krishnamurti & Subrahmanyam, 1982; Sikka & Gadgil, 1980). Such propagation has a typical latitudinal scale of thirty-degrees during a normal monsoon year (Chakraborty & Nanjundiah, 2012). Thus, it is necessary for the numerical models to accurately predict the MISO (Chattopadhyay et al., 2008).

In recent decades, there has been an increasing trend in the number of precipitation extremes over the tropics (Beniston & Stephenson, 2004; Mason et al., 1999) in general and India in particular (Goswami et al., 2006; Rajeevan et al., 2008; Dash et al. 2009, Roxy et al., 2017), and heat waves (Dash et al. 2011). This is associated with anthropogenic activities, particularly the rising temperatures on account of increased carbon-di-oxide in the atmosphere. The spatio-temporal characteristics of extreme events changes with the climate. It was shown that thermodynamic factors provide the necessary conditions for extreme rainfall. Recent studies highlight the importance of dynamics in altering the size and intensity of extreme events through feedback processes (Nikumbh et al., 2019).

The above mentioned spatio-temporal variations of monsoon rainfall affect the agriculture production and economy of the country (Sulochana Gadgil & Gadgil, 2006; Ladejinsky, 1973) and is critical for water resources management (Anshuman et al., 2019; Webster & Hoyos, 2004). Therefore, it is imperative to understand the monsoons from the viewpoints of basic theory, develop adequate models for their realistic representation, and make accurate forecasts as required by various users. Such goals can be achieved only when constructive collaborations are in place among different disciplines with adequate (a) long-term observations, (b) development of theories, and (c) building of models to accurately represent the system.

In the following sections, we present our current knowledge of these three crucial parts of monsoon research, intending to identify the gaps and thereby elicit research goals.

Observations

India is fortunate to have long-term observations of various climate parameters through stations spread all over the country. India Meteorological Department (IMD) established in 1875 is the National Meteorological Service of the country and the principal government agency in all matters relating to meteorology and allied subjects. The following mandate of IMD, as part of other important mandates, defines the importance of sustainable weather observations in the country and exchange globally: To take meteorological observations and to provide current and forecast meteorological information for optimum operation of weather-sensitive activities like agriculture, irrigation, shipping, aviation, offshore oil explorations, etc. It is imperative to quote Prof. Petteri Taalas, Secretary-General, WMO in this context: "These long-term measurements ... are the backbone of both weather forecasting and climate science. It is highly important that we ensure the long-term sustainability of these measurements."

The meteorological observational network across the country is the strongest point of IMD. Meteorology, as we perceive it now, may be said to have had its firm scientific foundation in the 17th century after the invention of the thermometer and the barometer and the formulation of laws governing the behaviour of atmospheric gases.

Long-term meteorological observations are part of the irreplaceable cultural and scientific heritage of mankind that serve the needs of current and future generations for long-term high-quality climate records. They are unique sources of past information about atmospheric parameters, thus are references for climate variability and change assessments.

The observational network over a period of more than 100 years have seen a significant adoption of Technology and Scientific Advancements. It included the observations on surface, upper air, Oceans too. Along with conventual met observatories, IMD has accommodated the instruments like AWS, ARG, ASG and AAWS etc. State of the art doppler radars and weather satellites, GPS based Upper air observations, AMDAR and sector specific customized high ended met Instruments in line with global technologies is continuous process in IMD under the guidance of MoES.

Densification of observational network is a big agenda in front of IMD, especially on the backdrop of Climate Change and its likely impact on the country and globally too. IMD has also presence in the Projects of WMO; GBON and RBON too. R & D in this sector is also parallel to meet the global standards and practices. Expansion of the observational network along with sustaining of existing network (historic too) is unending process.

Theory

The Indian monsoon rainfall is a coupled atmosphere-ocean-land phenomenon. The variability of the seasonal total, often termed as the Indian Summer Monsoon Rainfall (ISMR) is largely controlled by the slowly varying dominant modes of the climate system (Shukla, 1998). Teleconnection of the global climate is generally used to explain the interannual variations of ISMR. Among those, the role of equatorial ocean basin's zonal dipole had been the most dominant forcing for interannual variations of ISMR. The El Niño and Southern Oscillation (ENSO) of the Pacific Ocean is the most robust source of interannual predictability for ISMR (A. Chakraborty & Singhai, 2021; Rajeevan & Pai, 2007; Rasmusson & Carpenter, 1982; Webster & Yang, 1992). However, the strength of the ENSO-ISMR relationship varies at multi-decadal time scale (Bhupendra N. Goswami et al., 2016; Sinha et al., 2011; Srivastava et al., 2019). The coupled zonal mode of the equatorial Indian Ocean (Saji et al., 1999) and its atmospheric counterpart (Sulochana Gadgil et al., 2004) could also influence ISMR directly or through modifying the impact of ENSO (Ajayamohan et al., 2008; Ashok et al., 2004; Chakraborty & Singhai, 2021). The Atlantic Zonal Mode (AZM) could also impact ISMR modulating the climate of the upper troposphere (Krishnamurthy & Krishnamurthy, 2016; Kucharski et al., 2008; Yadav et al., 2018).

In contrast to the tropics, the midlatitude climate is associated with decadal time scale variations of ISMR. For example, the Pacific Decadal Oscillation (PDO) could impact ISMR in combination with ENSO (Krishnamurthy & Krishnamurthy, 2014; Krishnan & Sugi, 2003). The Atlantic Multidecadal Oscillation (AMO) (B. N. Goswami, Madhusoodanan, et al., 2006; Krishnamurthy & Krishnamurthy, 2016; Luo et al., 2011; Y. Wang et al., 2009; Zhang & Delworth, 2006), and the Southern Annular Mode (SAM) (Dwivedi et al., 2022; Prabhu et al., 2016) also influences ISMR on decadal time scales.

The most important slowly varying land-surface forcing to ISMR is possibly the Eurasian Snow Cover (Bamzai & Shukla, 1999; Hahn & Shukla, 1976; KRIPALANI et al., 1996) are also known to influence the variability of the ISMR on interannual to multi-decadal time scale. However, the role of land surface processes including its soil moisture content, vegetation cover, irrigation effects and urbanization impacts have received attention in recent researchers (Arindam Chakraborty et al., 2022; Chen et al., 2016; Saeed et al., 2009; Saha et al., 2011).

We probably correctly realize that variations in climate arise from interactions and energy exchange between multiple components (Cai et al., 2019; Meehl et al., 2001). However, the underlying physical mechanisms of the interaction that drive the scale selection and their coevolution remain elusive.

Our current understanding of the Monsoon at the subseasonal time scales is possibly somewhat better than the interannual variations of ISMR. Considerable amount of work has been done in the past that explains the antecedents of the onset of monsoon – that heralds the rainy season (Ananthakrishnan & Soman, 1988; P. v. Joseph et al., 2006; Krishnamurti et al., 1981; B. Wang et al., 2004). Theories have been proposed that explain onset as eddy-mediated regime change from heat low to dynamic low based on energetics of the atmosphere (Bordoni & Schneider, 2008; A. Chakraborty et al., 2006).

Similarly, several theories are proposed for the northward propagation of ITCZ at the 30-60-day time scale that brings active-break spells of monsoon (S. Joseph et al., 2009; Krishnan et al., 2000). These include baroclinic dynamics involving vertical shear of zonal wind (Jiang et al., 2004), and moisture-flux convergence (Nirupam Karmakar & Misra, 2020). In contrast, the westward propagating 10-20-day mode (KRISHNAMURTI & ARDANUY, 1980) has received relatively less attention to explain the physical mechanism (Chatterjee & Goswami, 2004; Ortega et al., 2017). At a smaller time-scale, the tropical synoptic systems could substantially alter the rainfall distribution over different parts of India with the formation and movement of monsoon lows and depressions (Ajayamohan et al., 2010; Hunt et al., 2016).

Currently, we reasonably understand the role played by these intraseasonal modes on the spatiotemporal distribution of rainfall within a season. However, our current understanding must provide a clearer picture of their interannual variations. Do these intraseasonal modes obtain energy from the seasonal mean large-scale climate? Or do these smaller scales determine the seasonal mean energetics? Only when such questions are answered satisfactorily will our knowledge of monsoons and their variability be more evident.

Simulation and Prediction

The skilful prediction of the ISMR on a seasonal to decadal time scale has remained one of the 'grand challenge' problems of climate science (Gadgil & Srinivasan, 2011; Rajeevan et al., 2012). Recently, the Climate Forecast System (CFSv2) model was deployed in India for the dynamical seasonal prediction of monsoon as a part of the National Monsoon Mission from the Ministry of Earth Sciences, Govt of India. This model provides an overall reasonable skill in the prediction of ISMR (Rao et al., 2019). However, notable improvements were made in the extended-range prediction of monsoon using ensemble prediction system (Abhilash et al., 2014). The facts that the relative importance of known predictable drivers of the ISMR is changing in recent decades on different time scales, calls for necessity of re-examining certain teleconnections of the ISMR and identification of new predictable drivers of the ISMR in a warming scenario.

Key Gap Areas

Although our understanding on monsoon characteristics and its prediction skills have improved substantially during the past several decades on account of extensive research and increasing of computing power, there remains several unanswered questions. Some of the gray areas of monsoon research includes:

a. Understanding the organization of multiscale nature of monsoon precipitation is not known adequately. Development of clouds under certain condition and its organization into large-scale weather disturbances involves energy exchange between multiple scales. Such interactions need to be represented by numerical models for accurate prediction of different phenomena like extreme rainfall events. This has been more relevant today in the backdrop of global warming.
b. Understanding global teleconnections to monsoon is key to prediction and access it from global context. Although we know the overall impact of ENSO on monsoon, which is mostly captured by most global models, prediction spatial patterns of rainfall anomaly during ENSO years still remain as poor as other years (Lee Drbohlav & Krishnamurthy, 2010). This suggest that we do not adequately understand the mechanism how ENSO impacts monsoon at regional scales. Another important teleconnection relationship is with non-ENSO forcings. The ENSO and non-ENSO teleconnections control the short to long term response of rainfall. Extratropical to tropical teleconnection is an active area of research in recent years. Extratropical Rossby wave intrusion provides forcing to the mean monsoon flow. It as been found that such intrusions are associated with extreme rainfall events, especially over the Himalayan region. Understanding such events would help to improve the relatively unexplored pathways of monsoon.

c. Improving the understanding the role of Indian Ocean, especially during ENSO neutral years, is important. Indian Summer Monsoon is influenced by local and remote forcing. The leading modes of Tropical Indo-Pacific Ocean is playing major role in controlling the ISM variability. When it comes to local forcing, basin wide warming and Indian Ocean Dipole (IOD) are leading mode of variability if Indian Ocean. For remote forcing El Niño and Southern Oscillation (ENSO) in Pacific Ocean is the dominant mode which are affecting monsoon. Apart from this, there are some extra tropical oceanic influence through Hadley circulation. These circulations are mainly control by Sothern Annular Mode (SAM) in southern hemisphere and in north-west Pacific the Pacific-Japan (PJ) pattern. The understanding of the relationship between IOD and ENSO with ISM is better explored than the extratropical influences like SAM and PJ pattern. This is a scope in future to investigate the impact of these extratropical modes in ISM and the state of art representation in the models or the forecasting systems.
d. Apart from this improving ENSO and IOD predictions is crucial to project large-scale climate variability as well as the ISM variability, which is great scientific interest and societal need. But due to large uncertainties in the simulated ENSO and IOD response the climate model forecast is difficult. Upcoming goal should be to understand and resolve this modelling challenges in an optimized way to get better representation of ISM in our forecasting system.
e. Understanding the role of land-surface on monsoon is another great challenge. Unlike ocean, land surface conditions can change within a very short time (through changes in vegetation and soil moisture). There are several studies those highlighted the role of land-atmosphere interaction on monsoon, especially over Indian land region and its surroundings. However, it is unclear how a sudden change (e.g., due to onset, or due to sub-seasonal drought/flood) can impact the overall monsoon. This requires details observation and modelling studies.

KEY OBJECTIVES

<u>The Grand Objective</u>

The primary and foremost objective should be reasonably accurate forecasts of monsoon precipitation. The time and space scales of the prediction are a matter of requirement (demand) and feasibility (supported by the current understanding of science and availability of resources).

It is not possible to understand and forecast monsoons without knowledge of the fundamental physical mechanism that drives it. Thus, basic research and numerical modelling are inseparable prerequisites to the key objective delineated above. At the same time, research in monsoon, especially its forecasting, should be useful to the society and help the country and the world in different sectors – at present and in the future. With this goal, we divided the specific objectives into three major categories: (a) process or theory based (b) model development or forecast skill based, and (c) application or utilization based. These are detailed below.

<u>Specific Objectives</u>

Process or theory-based objectives

I. Monsoon as a component of the global scale ITCZ: the Indian summer monsoon's seasonal evolution occurs along with the global (zonal mean) ITCZ. As yet, the variabilities of Indian summer monsoon rainfall are driven by several factors other than the large-scale hemispheric forcings. This could arise from zonal asymmetry and regional characteristics. It is necessary to understand the interaction between Indian monsoon and global mean ITCZ. This will pave the way for fixing errors in large-scale models.

II. Energetics of monsoon: Surface precipitation is the final product of a system consisting of coupled components and energy exchange. The large-scale driver of this system, thus, needs to be understood. A framework that is simple and decomposable is necessary to develop that will help cognize such complex systems driving monsoon.

III. Role of ENSO in driving spatial variations of monsoon precipitation: Indeed, we understand the underlying mechanism how ENSO impacts monsoon better than other climate drivers. However, this comprehension is limited to seasonal and spatial mean rainfall over Indian land. The real impact of monsoon on economy and livelihood comes from its spatial and sub-seasonal variations. However, current models, those can forecast ENSO-Monsoon correlation in a reasonably good fashion, fails measurably in predicting the spatial patterns of rainfall (Lee Drbohlav & Krishnamurthy, 2010). Thus, it is intriguing to understand the physical mechanism of spatial variations in monsoon rainfall teleconnection to ENSO.

IV. Understanding evolution of ENSO and its impact: ENSO, which is typically symmetric about the equator impacts monsoon that is asymmetric about the equator. Recent researches show that preceding winter ENSO condition can significantly impact summer monsoon precipitation, especially during ENSO-neutral years and it is more prominent during extreme drought years (Chakraborty, 2018). Thus, it is necessary to know the interaction of seasonal evolution of ENSO and monsoon and their forcing on each other.

V. Understanding tropical non-ENSO teleconnections: Non-ENSO linked teleconnection are generally weak in the presence of ENSO but can affect monsoon significantly during ENSO neutral years. Such forcing involves tropical Indian ocean variability, tropical Atlantic Ocean variability.

VI. Tropical-extratropical interaction: How extratropic influences tropical climate has long been studied but less understood. It is necessary to know such interactions for monsoon climate.

VII. Role of land surface in the amplification of the monsoon systems in the subseasonal scale: The land use and land cover change in several regions of India is drastic and the impact of urbanization over the Indian region has increased the risk of disasters and extreme events. It is not clear on how monsoon system response to such micro level forcing.

VIII. Understanding the seasonal shifting: the interannual variability of monsoon has pronounced seasonality. The June-September rainfall is so far taken as the season of the monsoonal rainfall. In recent years studies have shown significant rainfall during October especially in the first half when the withdrawal of rainfall does not occur over the Indian region. Such shifting or stretching of seasonal cycle is important to understand the interannual variability especially the causal attribution of the same in terms of anthropogenic forcing. It is important to find out whether such temporal shift in season is noted in other years also, and is there a significant trend in the shifting of the season. Over North America, studies show that there is a significant delay in all the stages (beginning, peak and closing) of monsoon in recent decades. During the early stages of monsoon, such a delay is attributed to the enhanced antecedent wetness during winter-spring time delaying the seasonal heating of the North American continent resulting in delayed monsoon initiation.

IX. Regional variability and near long terms trends in monsoon. The monsoon shows shifts in rainfall patterns over different states of India. In recent years, some of the rice-producing states received less seasonal quantum of rainfall, even though the seasonal mean remains the same on an Indian basis. It is necessary to understand the processes leading to this uneven trend in space.

X. Clouds, convection and microphysical processes: Compared to other areas, clouds and convection has received less attention from Indian researchers. Given that convection is in the center to monsoons, it is necessary to get stronger hold of these processes. Dedicated planning for observations in cloud processes and joint modelling studies would benefit this field immensely.

Model Development or Forecast Skill based objectives

XI. Development of statistical-physical based cloud modelling: Cloud processes are smaller in space than a reasonable global model with reasonable resolution can handle with operational forecasting. Thus, cloud processes will remain parameterized for a long time to come. Moreover, many details of these processes including energetics and microphysics are unknown. A statistical viewpoint for the cloud and convection parameterization could help here (Arakawa, 2004). In India, researchers should give thrust in this important area of development that will result in better understanding of the monsoon and its forecasting.

XII. Improve modelling of air-sea interactions: Most of the current coupled models have cold sea surface temperature bias. While part of the problem could arise from errors in the ocean model and in the atmosphere model, air-sea interaction and related fluxes could play vital role in the process. Dedicated efforts of observation and modelling could be made to solve this problem.

XIII. Development of interactive vegetation model: Land-atmosphere interaction is an important area of research. Yet, this field has grown somewhat unstructured due to lack of joint efforts by observers and modelers. In India, developing interactive vegetation models is important as the country experiences constant change in land use and agriculture practices.

XIV. Applicability of data driven methods: Several data driven machine learning approach is coming up in the recent decades. Data driven methods are useful and can provide several guidance relevant to model data post-processing, downscaling, impact-based forecasting etc. Several works are currently reported based on data driven methods. These methods although are data dependent, are successful in several applications like downscaling, nowcasting, short-range forecasting etc.

Application or utilization-based objectives

XV. Improving the impact-based forecasting of monsoon on regional scale: The monsoon forecast continues to improve with the incorporation of several modelling strategies. The synoptic to intraseasonal forecasting shows remarkable improvement in the recent decades. However, these forecasts are more tuned to predict the quantum of rainfall and the spatial pattern. The current requirement of forecasting applications indicates that the microlevel management of climate sensitive sectors require application specific impact or risk outlooks. Hence development of an impact-based forecast system for different applications has become a necessity.

ROADMAP

Indian summer monsoon probably is the most critical and complex climate system to understand and predict. While monsoon relates to numerous physical processes having time scale ranging from milliseconds to millennium and space scales ranging from micrometers to planetary, the importance of monsoon rainfall is also enormous for the livelihood of the country. Comprehension and prediction of monsoon is thus an evolving field that requires short-term planning and long-term vision. We delineate here a few steps we feel necessary to advance monsoon research and prediction during the next decade, and later take it further to make Indian monsoon research and prediction the best in the world.

Short-term (by 2030)

I. Set up dynamic groups of researchers in the country to work on themes like observations, land-surface, boundary layer, cloud physics, ocean components of the model. These groups can collaborate among each other.
II. Establish strong connections between groups of observations and modelers. This will be key to the overall understanding of the monsoon.
III. Develop a RADAR network and program in cloud physics.
IV. Establish AWS network over India that is equally dense over each part of the country. It is also necessary to enhance observations over Andaman and Nicobar Island.
V. No field can develop without involvement of private industry. Fortunately, monsoon prediction has several applications where private farms can be interested. This also ensures increase of job opportunity. It is necessary to plan forecasts such that it could be useful to the private farms. This can be achieved through discussions and feedbacks.
VI. All model simulations should be available online free of cost to all. This will provide opportunity to several researchers throughout the globe to use Indian models and in turn benefit model development.

Long-Term (Beyond 2030)

I. Develop new earth system models.
II. Develop land-surface model with interactive components like vegetation and irrigation.
III. Structured study of the monsoon system: Understanding the mechanism of monsoons involves multidisciplinary views like radiation, thermodynamics, dynamics, chemistry, and mathematics.
IV. Establish a simple theoretical framework that can explain interannual variations of the Indian summer monsoon precipitation.
V. Understand region specific interaction between land and atmosphere. This can be done with dedicated and enhanced observations along with modelling experiments.
VI. Understand the thermodynamic and dynamic factors affecting precipitation over different regions. This will entail collaborative research between groups of observations and modelers.
VII. Understand linkage between different components of monsoon from cloud scale to large-scale teleconnection.

REFERENCES

Abhilash, S., Sahai, A. K., Pattnaik, S., Goswami, B. N., & Kumar, A. (2014). Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System. *International Journal of Climatology*, *34*(1), 98–113. https://doi.org/10.1002/joc.3668

Adam, O., Bischoff, T., & Schneider, T. (2016). Seasonal and interannual variations of the energy flux equator and ITCZ. Part I: Zonally averaged ITCZ position. *Journal of Climate*, *29*(9), 3219–3230. https://doi.org/10.1175/JCLI-D-15-0512.1

Ajayamohan, R. S., Rao, S. A., & Yamagata, T. (2008). Influence of Indian ocean dipole on poleward propagation of boreal summer intraseasonal oscillations. *Journal of Climate*, *21*(21), 5437–5454. https://doi.org/10.1175/2008JCLI1758.1

Ajayamohan, R. S., Merryfield, W. J., & Kharin, V. v. (2010). Increasing Trend of Synoptic Activity and Its Relationship with Extreme Rain Events over Central India. *Journal of Climate*, *23*(4), 1004–1013. https://doi.org/10.1175/2009JCLI2918.1

Ananthakrishnan, R., & Soman, M. K. (1988). The onset of the southwest monsoon over Kerala: 1901-1980. *Journal of Climatology*, *8*(3), 283–296. https://doi.org/10.1002/joc.3370080305

Anshuman, A., Kunnath-Poovakka, A., & Eldho, T. I. (2019). Towards the use of conceptual models for water resource assessment in Indian tropical watersheds under monsoon-driven climatic conditions. *Environmental Earth Sciences*, *78*(9), 282. https://doi.org/10.1007/s12665-019-8281-5

Arakawa, A. (2004). The Cumulus Parameterization Problem: Past, Present, and Future. *Journal of Climate*, *17*(13), 2493–2525. https://doi.org/10.1175/1520-0442(2004)017<2493:RATCPP>2.0.CO;2

Ashok, K., Guan, Z., Saji, N. H., & Yamagata, T. (2004). Individual and Combined Influences of ENSO and the Indian Ocean Dipole on the Indian Summer Monsoon. *Journal of Climate*, *17*(16), 3141–3155. https://doi.org/10.1175/1520-0442(2004)017<3141:IACIOE>2.0.CO;2

Bamzai, A. S., & Shukla, J. (1999). Relation between Eurasian Snow Cover, Snow Depth, and the Indian Summer Monsoon: An Observational Study. *Journal of Climate*, *12*(10), 3117–3132. https://doi.org/10.1175/1520-0442(1999)012<3117:RBESCS>2.0.CO;2

Beniston, M., & Stephenson, D. B. (2004). Extreme climatic events and their evolution under changing climatic conditions. *Global and Planetary Change*, *44*(1–4), 1–9. https://doi.org/10.1016/j.gloplacha.2004.06.001

Biasutti, M., Voigt, A., Boos, W. R., Braconnot, P., Hargreaves, J. C., Harrison, S. P., et al. (2018). Global energetics and local physics as drivers of past, present and future monsoons. *Nature Geoscience*, *11*(6), 392–400. https://doi.org/10.1038/s41561-018-0137-1

Bordoni, S., & Schneider, T. (2008). Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience*, *1*(8), 515–519. https://doi.org/10.1038/ngeo248

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., et al. (2019). Pantropical climate interactions. *Science*, *363*(6430). https://doi.org/10.1126/science.aav4236

Chakraborty, A., & Nanjundiah, R. S. (2012). Space-time scales of northward propagation of convection during boreal summer. *Monthly Weather Review*, *140*(12). https://doi.org/10.1175/MWR-D-12-00088.1

Chakraborty, A., & Singhai, P. (2021). Asymmetric response of the Indian summer monsoon to positive and negative phases of major tropical climate patterns. *Scientific Reports*, *11*(1), 22561. https://doi.org/10.1038/s41598-021-01758-6

Chakraborty, A., Nanjundiah, R. S., & Srinivasan, J. (2006). Theoretical aspects of the onset of Indian summer monsoon from perturbed orography simulations in a GCM. *Annales Geophysicae*, *24*(8), 2075–2089. https://doi.org/10.5194/angeo-24-2075-2006

Chakraborty, Arindam, Samuel, J. B., & Paleri, A. (2022). Role of land-surface vegetation in the march of Indian monsoon onset isochrones in a coupled model. *Quarterly Journal of the Royal Meteorological Society*. https://doi.org/10.1002/qj.4398

Chatterjee, P., & Goswami, B. N. (2004). Structure, genesis and scale selection of the tropical quasi-biweekly mode. *Quarterly Journal of the Royal Meteorological Society*, *130*(599 PART B), 1171–1194. https://doi.org/10.1256/qj.03.133

Chattopadhyay, R., Sahai, A. K., & Goswami, B. N. (2008). Objective identification of nonlinear convectively coupled phases of monsoon intraseasonal oscillation: Implications for prediction. *Journal of the Atmospheric Sciences*, *65*(5), 1549–1569. https://doi.org/10.1175/2007JAS2474.1

Chen, H., Zhang, Y., Yu, M., Hua, W., Sun, S., Li, X., & Gao, C. (2016). Large-scale urbanization effects on eastern Asian summer monsoon circulation and climate. *Climate Dynamics*, *47*(1–2), 117–136. https://doi.org/10.1007/s00382-015-2827-3

Dash, S. K., and Ashu Mamgain. (2011) "Changes in the frequency of different categories of temperature extremes in India." *Journal of Applied Meteorology and Climatology* 50.9: 1842-1858.

Dash, S. K., et al. (2009) "Changes in the characteristics of rain events in India." *Journal of Geophysical Research: Atmospheres* 114.D10.

Donohoe, A., Marshall, J., Ferreira, D., & Mcgee, D. (2013). The Relationship between ITCZ Location and Cross-Equatorial Atmospheric Heat Transport: From the Seasonal Cycle to the Last Glacial Maximum. *Journal of Climate*, *26*(11), 3597–3618. https://doi.org/10.1175/JCLI-D-12-00467.1

Dwivedi, S., Pandey, P., & Goswami, B. N. (2022). Nonstationarity and potential multi-decadal variability in Indian Summer Monsoon Rainfall and Southern Annular Mode teleconnection. *Climate Dynamics*, *59*(3–4), 671–683. https://doi.org/10.1007/s00382-022-06146-y

Gadgil, S, & Srinivasan, J. (2011). Seasonal prediction of the Indian monsoon. *Current Science*, *100*, 343–353.

Gadgil, Sulochana. (2003). The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, *31*, 429–467. https://doi.org/10.1146/annurev.earth.31.100901.141251

Gadgil, Sulochana, & Gadgil, S. (2006). The Indian Monsoon, GDP and Agriculture. *Economic and Political Weekly*, *41*(47), 4887+4889-4895. Retrieved from https://www.jstor.org/stable/4418949#metadata_info_tab_contents

Gadgil, Sulochana, Vinayachandran, P. N., Francis, P. A., & Gadgil, S. (2004). Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophysical Research Letters*, *31*(12), n/a-n/a. https://doi.org/10.1029/2004GL019733

Goswami, B. N. (2006). The Asian monsoon: Interdecadal variability. In *The Asian Monsoon* (pp. 295–327). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-37722-0_7

Goswami, B. N., Madhusoodanan, M. S., Neema, C. P., & Sengupta, D. (2006). A physical mechanism for North Atlantic SST influence on the Indian summer monsoon. *Geophysical Research Letters*, *33*(2), L02706. https://doi.org/10.1029/2005GL024803

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing Trend of Extreme Rain Events Over India in a Warming Environment. *Science*, *314*(5804), 1442–1445. https://doi.org/10.1126/science.1132027

Goswami, Bhupendra N., Kripalani, R. H., Borgaonkar, H. P., & Preethi, B. (2016). Multi-Decadal Variability in Indian Summer Monsoon Rainfall Using Proxy Data. *World Scientific Series on Asia-Pacific Weather and Climate*, *6*, 327–345. https://doi.org/10.1142/9789814579933_0021

Hahn, D. G., & Shukla, J. (1976). An Apparent Relationship between Eurasian Snow Cover and Indian Monsoon Rainfall. *Journal of the Atmospheric Sciences*, *33*(12), 2461–2462. https://doi.org/10.1175/1520-0469(1976)033<2461:AARBES>2.0.CO;2

Hunt, K. M. R., Turner, A. G., & Parker, D. E. (2016). The spatiotemporal structure of precipitation in Indian monsoon depressions. *Quarterly Journal of the Royal Meteorological Society*, *142*(701), 3195–3210. https://doi.org/10.1002/qj.2901

Jiang, X., Li, T., & Wang, B. (2004). Structures and Mechanisms of the Northward Propagating Boreal Summer Intraseasonal Oscillation*. *Journal of Climate*, *17*(5), 1022–1039. https://doi.org/10.1175/1520-0442(2004)017<1022:SAMOTN>2.0.CO;2

Joseph, P. v., Sooraj, K. P., & Rajan, C. K. (2006). The summer monsoon onset process over South Asia and an objective method for the date of monsoon onset over Kerala. *International Journal of Climatology*, *26*(13), 1871–1893. https://doi.org/10.1002/joc.1340

Joseph, S., Sahai, A. K., & Goswami, B. N. (2009). Eastward propagating MJO during boreal summer and Indian monsoon droughts. *Climate Dynamics*, *32*(7–8), 1139–1153. https://doi.org/10.1007/s00382-008-0412-8

Kang, S. M., Held, I. M., Frierson, D. M. W., & Zhao, M. (2008). The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *Journal of Climate*, *21*(14), 3521–3532. https://doi.org/10.1175/2007JCLI2146.1

Karmakar, N., Chakraborty, A., & Nanjundiah, R. S. (2020). Influence of global sea-surface temperature on ultra-low-frequency variability in Indian summer monsoon rainfall. *Quarterly Journal of the Royal Meteorological Society*, *146*(727). https://doi.org/10.1002/qj.3715

Karmakar, Nirupam, & Misra, V. (2020). Differences in Northward Propagation of Convection Over the Arabian Sea and Bay of Bengal During Boreal Summer. *Journal of Geophysical Research: Atmospheres*, *125*(3). https://doi.org/10.1029/2019JD031648

KRIPALANI, R. H., SINGH, S. v., VERNEKAR, A. D., & THAPLIYAL, V. (1996). EMPIRIACAL STUDY ON NIMBUS-7 SNOW MASS AND INDIAN SUMMER MONSOON RAINFALL. *International Journal of Climatology*, *16*(1), 23–34. https://doi.org/10.1002/(SICI)1097-0088(199601)16:1<23::AID-JOC988>3.0.CO;2-J

Krishnamurthy, L., & Krishnamurthy, V. (2016). Teleconnections of Indian monsoon rainfall with AMO and Atlantic tripole. *Climate Dynamics*, *46*(7–8), 2269–2285. https://doi.org/10.1007/s00382-015-2701-3

Krishnamurthy, Lakshmi, & Krishnamurthy, V. (2014). Influence of PDO on South Asian summer monsoon and monsoon–ENSO relation. *Climate Dynamics*, *42*(9–10), 2397–2410. https://doi.org/10.1007/s00382-013-1856-z

KRISHNAMURTI, T. N., & ARDANUY, P. (1980). The 10 to 20-day westward propagating mode and "Breaks in the Monsoons." *Tellus*, *32*(1), 15–26. https://doi.org/10.1111/j.2153-3490.1980.tb01717.x

Krishnamurti, T. N., & Subrahmanyam, D. (1982). The 30–50 Day Mode at 850 mb During MONEX. *Journal of the Atmospheric Sciences*, *39*(9), 2088–2095. https://doi.org/10.1175/1520-0469(1982)039<2088:TDMAMD>2.0.CO;2

Krishnamurti, T. N., Ardanuy, P., Ramanathan, Y., & Pasch, R. (1981). On the Onset Vortex of the Summer Monsoon. *Monthly Weather Review*, *109*(2), 344–363. https://doi.org/10.1175/1520-0493(1981)109<0344:OTOVOT>2.0.CO;2

Krishnan, R., & Sugi, M. (2003). Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. *Climate Dynamics*, *21*(3–4), 233–242. https://doi.org/10.1007/s00382-003-0330-8

Krishnan, R., Zhang, C., & Sugi, M. (2000). Dynamics of Breaks in the Indian Summer Monsoon. *Journal of the Atmospheric Sciences*, *57*(9), 1354–1372. https://doi.org/10.1175/1520-0469(2000)057<1354:DOBITI>2.0.CO;2

Kucharski, F., Bracco, A., Yoo, J. H., & Molteni, F. (2008). Atlantic forced component of the Indian monsoon interannual variability. *Geophysical Research Letters*, *35*(4), L04706. https://doi.org/10.1029/2007GL033037

Ladejinsky, W. (1973). Drought in Maharashtra (Not in a Hundred Years) . *Economic and Political Weekly*, *8*(7), 383+385+387-389+391+393-396.

Lee Drbohlav, H.-K., & Krishnamurthy, V. (2010). Spatial Structure, Forecast Errors, and Predictability of the South Asian Monsoon in CFS Monthly Retrospective Forecasts. *Journal of Climate*, *23*(18), 4750–4769. https://doi.org/10.1175/2010JCLI2356.1

Luo, F., Li, S., & Furevik, T. (2011). The connection between the Atlantic Multidecadal Oscillation and the Indian Summer Monsoon in Bergen Climate Model Version 2.0. *Journal of Geophysical Research*, *116*(D19), D19117. https://doi.org/10.1029/2011JD015848

Mason, S. J., Waylen, P. R., Mimmack, G. M., Rajaratnam, B., & Harrison, J. M. (1999). *CHANGES IN EXTREME RAINFALL EVENTS IN SOUTH AFRICA*. https://doi.org/10.1023/A:1005450924499

Meehl, G. A., Lukas, R., Kiladis, G. N., Weickmann, K. M., Matthews, A. J., & Wheeler, M. (2001). A conceptual framework for time and space scale interactions in the climate system. *Climate Dynamics*, *17*(10), 753–775. https://doi.org/10.1007/s003820000143

Nikumbh, A. C., Chakraborty, A., & Bhat, G. S. (2019). Recent spatial aggregation tendency of rainfall extremes over India. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-46719-2

Ortega, S., Webster, P. J., Toma, V., & Chang, H.-R. (2017). Quasi-biweekly oscillations of the South Asian monsoon and its co-evolution in the upper and lower troposphere. *Climate Dynamics*, *49*(9–10), 3159–3174. https://doi.org/10.1007/s00382-016-3503-y

Prabhu, A., Kripalani, R. H., Preethi, B., & Pandithurai, G. (2016). Potential role of the February–March Southern Annular Mode on the Indian summer monsoon rainfall: a new perspective. *Climate Dynamics*, *47*(3–4), 1161–1179. https://doi.org/10.1007/s00382-015-2894-5

Preethi, B., Ramya, R., Patwardhan, S. K., Mujumdar, M., & Kripalani, R. H. (2019). Variability of Indian summer monsoon droughts in CMIP5 climate models. *Climate Dynamics*, *53*(3–4), 1937–1962. https://doi.org/10.1007/s00382-019-04752-x

Rajeevan, M., & Pai, D. S. (2007). On the El Niño-Indian monsoon predictive relationships. *Geophysical Research Letters*, *34*(4), L04704. https://doi.org/10.1029/2006GL028916

Rajeevan, M., Bhate, J., & Jaswal, A. K. (2008). Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophysical Research Letters*, *35*(18). https://doi.org/10.1029/2008GL035143

Rajeevan, M., Unnikrishnan, C. K., & Preethi, B. (2012). Evaluation of the ENSEMBLES multi-model seasonal forecasts of Indian summer monsoon variability. *Climate Dynamics*, *38*(11–12), 2257–2274. https://doi.org/10.1007/s00382-011-1061-x

Rao, S. A., Goswami, B. N., Sahai, A. K., Rajagopal, E. N., Mukhopadhyay, P., Rajeevan, M., et al. (2019). Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bulletin of the American Meteorological Society*, *100*(12), 2509–2532. https://doi.org/10.1175/BAMS-D-17-0330.1

Rasmusson, E. M., & Carpenter, T. H. (1982). Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño. *Monthly Weather Review*, *110*(5), 354–384. https://doi.org/10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2

Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., et al. (2017). A threefold rise in widespread extreme rain events over central India. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-00744-9

Saeed, F., Hagemann, S., & Jacob, D. (2009). Impact of irrigation on the South Asian summer monsoon. *Geophysical Research Letters*, *36*(20). https://doi.org/10.1029/2009GL040625

Saha, S. K., Halder, S., Kumar, K. K., & Goswami, B. N. (2011). Pre-onset land surface processes and ‘internal’ interannual variabilities of the Indian summer monsoon. *Climate Dynamics*, *36*(11–12), 2077–2089. https://doi.org/10.1007/s00382-010-0886-z

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, *401*(6751), 360–363. https://doi.org/10.1038/43854

Shukla, J. (1998). Predictability in the Midst of Chaos: A Scientific Basis for Climate Forecasting. *Science*, *282*(5389), 728–731. https://doi.org/10.1126/science.282.5389.728 PMID - 9784127

Sikka, D. R., & Gadgil, S. (1980). On the Maximum Cloud Zone and the ITCZ over Indian, Longitudes during the Southwest Monsoon. *Monthly Weather Review*, *108*(11), 1840–1853. https://doi.org/10.1175/1520-0493(1980)108<1840:OTMCZA>2.0.CO;2

Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R. L., Buckley, B., et al. (2011). A global context for megadroughts in monsoon Asia during the past millennium. *Quaternary Science Reviews*, *30*(1–2), 47–62. https://doi.org/10.1016/J.QUASCIREV.2010.10.005

Sinha, A., Kathayat, G., Cheng, H., Breitenbach, S. F. M., Berkelhammer, M., Mudelsee, M., et al. (2015). Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. *Nature Communications*, *6*. https://doi.org/10.1038/ncomms7309

Srivastava, G., Chakraborty, A., & Nanjundiah, R. S. (2019). Multidecadal see-saw of the impact of ENSO on Indian and West African summer monsoon rainfall. *Climate Dynamics*, *52*(11). https://doi.org/10.1007/s00382-018-4535-2

Wang, B., LinHo, Zhang, Y., & Lu, M.-M. (2004). Definition of South China Sea Monsoon Onset and Commencement of the East Asia Summer Monsoon*. *Journal of Climate*, *17*(4), 699–710. https://doi.org/10.1175/2932.1

Wang, Y., Li, S., & Luo, D. (2009). Seasonal response of Asian monsoonal climate to the Atlantic Multidecadal Oscillation. *Journal of Geophysical Research*, *114*(D2), D02112. https://doi.org/10.1029/2008JD010929

Webster, P. J., & Hoyos, C. (2004). Prediction of Monsoon Rainfall and River Discharge on 15–30-Day Time Scales. *Bulletin of the American Meteorological Society*, *85*(11), 1745–1766. https://doi.org/10.1175/BAMS-85-11-1745

Webster, P. J., & Yang, S. (1992). Monsoon and Enso: Selectively Interactive Systems. *Quarterly Journal of the Royal Meteorological Society*, *118*(507), 877–926. https://doi.org/10.1002/qj.49711850705

Yadav, R. K., Srinivas, G., & Chowdary, J. S. (2018). Atlantic Niño modulation of the Indian summer monsoon through Asian jet. *Npj Climate and Atmospheric Science*, *1*(1), 23. https://doi.org/10.1038/s41612-018-0029-5

Zhang, R., & Delworth, T. L. (2006). Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters*, *33*(17), L17712. https://doi.org/10.1029/2006GL026267

CHAPTER 2: CLIMATE MODELLING

Pankaj Kumar, Arindam Chakraborty, Saroj K Mishra, V S Prasad

Coordinating Lead Author
Prof. Pankaj Kumar, IISER Bhopal

Lead Authors
Prof. Arindam Chakraborty, IISc Bangalore
Prof. Saroj Kanta Mishra, IIT Delhi
Dr. V S Prasad, National Centre for Medium Range Weather Forecasting Noida

BACKGROUND

A climate model is the most critical tool to understand the global climate with implicit variability and anthropogenic change on various spatiotemporal scales. The observed variability at the seasonal, yearly, and decadal time scales supports the notion that human activity has "very likely" altered the global mean climate. This has raised critical questions about how vulnerable we are to numerous aspects of this observed climate variability and its embedded extremes. There has been various analysis, assessments, interpretations and many summaries on climate variability and extremes and on broad scale climate change that have been published so far, which gives a more precise depiction of how various environmental parameters, such as precipitation, humidity, winds, soil moisture, surface temperature etc. is varying and will vary further over time. Notably, the pattern and degree of these environmental parameter's variabilities have a high dependence on the time or space scales being examined and also on the responses/feedback within the climate system, such as varying atmospheric composition (e.g., with greenhouse gas emissions and volcanic activity), large-scale climate modes (like El Niño Southern Oscillation; ENSO and Indian Ocean Dipole; IOD), air-sea interaction feedback over tropics, biophysical state of the land surface, oceans, sea ice and ice sheets, etc. The differences in local land-atmosphere feedbacks, atmospheric circulation and other local elements, in addition to the aforementioned climatic responses and feedbacks, contribute to enhanced climate variability at the regional scale (defined here as subcontinents or a country).

The Intergovernmental Panel on Climate Change (IPCC) provides scientific assessments of climate change, its impacts, and potential solutions. IPCC Assessment Reports (ARs), are released periodically and provide a comprehensive assessment of the state of climate science. In the last two decades, three ARs came out, namely AR4 (2007), AR5 (2013) and AR6 (2021). The key findings in each report have also evolved over time. AR4 reported that the warming of the climate system was unequivocal and that most of the observed warming over the previous 50 years was due to human activities. AR5 highlighted that climate change was occurring faster and with greater severity than previously thought. It also noted the growing impacts on human societies, ecosystems, and economies. The AR6 emphasizes the dramatic increase in extreme weather events, the worsening of some climate impacts, and the narrowing of the window of opportunity to limit warming to 1.5°C.

The fundamental principle of fluid dynamics and thermodynamics is the foundation of Global Climate Models (GCMs), a mathematical model of climate systems and their interactions. To date, Global climate models are being developed and continually improved to study the past and future of Earth's climate system based on a few assumptions that the factors driving climate change will continue to evolve. These drivers are both natural and man-made, for example, the concentration of greenhouse gases in the atmosphere, volcanic eruption, amount and distribution of aerosols, land use and land cover etc. As part of IPCC AR4 report used four scenario families, including A1, A2, B1, and B2. The AR5 report introduced a new set of scenarios, referred to as Representative Concentration Pathways (RCPs), which included RCP2.6, RCP4.5, RCP6, and RCP8.5. The AR6 report used a new set of scenarios, referred to as Shared Socioeconomic Pathways (SSPs), which provide five different socioeconomic pathways, including SSP1, SSP2, SSP3, SSP4, and SSP5. The emission scenarios in the AR6 report were developed with a specific target of limiting global warming to 1.5°C above pre-industrial levels, in line with the Paris Agreement. This is a more ambitious target than in previous reports, which did not specify a temperature target. The different scenarios in each report also make different assumptions about socioeconomic factors, such as population growth, economic development, and energy use. For example, the AR4's A1 scenario assumes rapid economic growth and the adoption of new technologies, while the AR6's SSP1 scenario assumes a sustainable development path that promotes equality, health, and education.

GCMs are sophisticated coupled atmosphere-ocean General Circulation Models employed for studying the global climate and its underlying mechanisms. The new set of models called ESM, on the other hand, stands for Earth System Model, which is a more comprehensive model that incorporates not only the physical processes of the climate system but also the interactions between the climate system and other components of the Earth system, such as the biosphere and the carbon cycle. ESMs can simulate both the past and future climate, and can be used to investigate the impacts of various climate change scenarios on the Earth system as a whole. Technically, GCMs are more focused on simulating the physical processes of the climate system, while ESMs incorporate a more comprehensive representation of the Earth system as a whole. The World Climate Research Program (WCRP)'s Coupled Model Intercomparison Project (CMIP) is a database facility of several GCM/ESM (hereafter called either GCMs or ESMs) simulations extensively used for climate change studies worldwide. IPCC consider these simulations for preparing its assessment reports (AR4/AR5/AR6). Due to constraints in the individual ESM skills and the ESM model structure, both sources of uncertainty, generally large ensembles of ESMs are employed for future projection in all IPCC reports. However, because of the model and scenario uncertainty, the projected changes in the global mean temperature are spread out more widely, ranging between 1.5 °C and 4.5 °C in 2100. Additionally, AR6 report were developed with a specific target of limiting global warming to 1.5°C above pre-industrial levels

Recently, CMIP6 simulations have been conducted following shared socio-economic pathways to enhance our understanding by improving scenarios. In this CMIP6 simulation protocol, an ESM from the Indian Institute of Tropical Meteorology (IITM), namely (IITM-ESM) version-2, has participated. IITM-ESM completes 300-year spin-up and 500-year pre-industrial control simulations, Swapna et al. 2018 provide a summary of the findings. In addition, historical simulations and climate sensitivity runs has been performed covering the period 1850-2014.

Despite numerous efforts to improve model physics and further enhance model horizontal resolution compared to the previous CMIP versions (Taylor et al. 2012 and CMIP3; Meehl et al. 2007; Mishra et al. 2018; Jain et al. 2019), the CMIP6 (Stockhause and Lautenschlager 2017) simulations still lack in resolving local climatic processes, particularly in the complex regions. In the tropics, a large inter-model spread further questions the confidence to project regional climate signals using these model setups (Kumar et al., 2013, 2014a, 2014b; Hu et al.,2017; Li et al., 2018; Wu et al., 2019).

Regardless of several advancements in GCMs or ESMs, it has several other constraints which restrict their use for studying various aspects of monsoon (Fu et al. 2007; Mishra et al. 2018), such as extreme events, low-pressure systems (Stowasser et al. 2009; Levine et al. 2018), teleconnection mechanisms (Srivastava et al. 2019), active- break spells in the monsoon systems (Sharmila et al. 2015; Misra et al. 2018), the boreal summer intraseasonal oscillation's movement (Sabeerali et al. 2013) etc. These limitations are reportedly due to the absence of adequate air-sea interaction at the regional scale, because of coarser model resolution.

Numerous studies on the Indian Monsoon using GCMs reached to a common conclusion that GCMs have difficulty reproducing India's typical monsoon climate (Goswami B. N., 1998; Rajeevan and Nanjundiah, 2009; Kodra et al., 2012; Turner and Annamalai, 2012; Pathak et al., 2019).

Though GCMs/ESMS can effectively describe the response of forcing, such as due to solar radiation or greenhouse gas but shows limitations to translate this effect to a finer level due to the complex topography, coastlines, land cover distribution, inland water bodies etc., for example, they cannot accurately simulate the complex orographic precipitation over India (Kumar et al., 2013; Jain et al., 2019). To overcome this limitation of global models, dynamical downscaling is used to translate spatially and temporally consistent GCM information to a regional scale using Regional Climate Model (RCM). In addition, high-resolution RCMs refined the information nested within GCMs, accounting for the effect of mesoscale processes concerning the topographical structures, coastlines, land use, and more clearly defined spatial gradients in physical fields (Jacob, 1997, 2001,2009; Giorgi,2002,2006). meanwhile, large-scale climate modes (IOD, ENSO etc.) are taken from the host GCMs.

The high-resolution RCMs more precisely depict the regional orographic features, Figure 2.1, and can therefore simulate better precipitation climatology compared to observations (IMD), the coarse horizontal resolution GCMs exhibit limits in capturing the regional orographic features. The relevance of local feedback mechanisms e.g. snow-albedo/air temperature or soil moisture/air temperature feedback is highlighted by the fact that this missing information from GCMs has a major impact on regional flow patterns. By addressing the said constraints, RCMs generally improve the statistics of the simulated meteorological variables at the regional scale compared to the observations. Noticing this prompted statistics, RCM has grown tremendously. However, the high demand for computer resources for RCMs poses a potential disadvantage and are sharply debated. Despite this, dynamical downscaling approaches are being used more frequently and are being improved.

Several RCM studies have been conducted to simulate the South Asian summer monsoon. In comparison to coarser global models, all have indicated an improvement in the simulation of spatiotemporal distribution, but they have also revealed orographic rainfall overestimation (Bhaskaran et al., 1996; Jacob and Podzum, 1997; Ji and Vernekar, 1997; Ratnam and Kumar, 2005; Das et al., 2006; Dobler and Ahrens, 2010; Lucas-Picher et al., 2011; Moors et al., 2012; Mathison et al., 2013; Dimri et al., 2013; Kumar et al. 2013,2014a,2014b).

In comparison to the South Asia-focused coordinated regional downscaling experiments (CORDEX-SA), the efficiency of the individually developed RCM has also been the subject of numerous research. Some of the attempts show more accurate simulation of the spatial distribution of the amount and intensity of the precipitation with some substantial dry bias across Central India (Dash et al.

201a,2015b; Kumar et al. 2014a,2014b; Pattnayak et al. 2018; Mishra et al. 2020a, b,2021a,2021b; Mishra and Dubey 2021).

In addition, few studies noted that the absence of air-sea interaction and feedback processes at the local scale in RCMs also hampers the simulation of strongly coupled processes like the Indian summer monsoon. This demonstrates the need for Regional Earth System Model to effectively simulate the interactions between various climate system components during the ISM (Ratnam et al. 2009; Kumar et al. 2013,2014a,2014b, 2014c; Giorgi 2019; Xue et al. 2020).

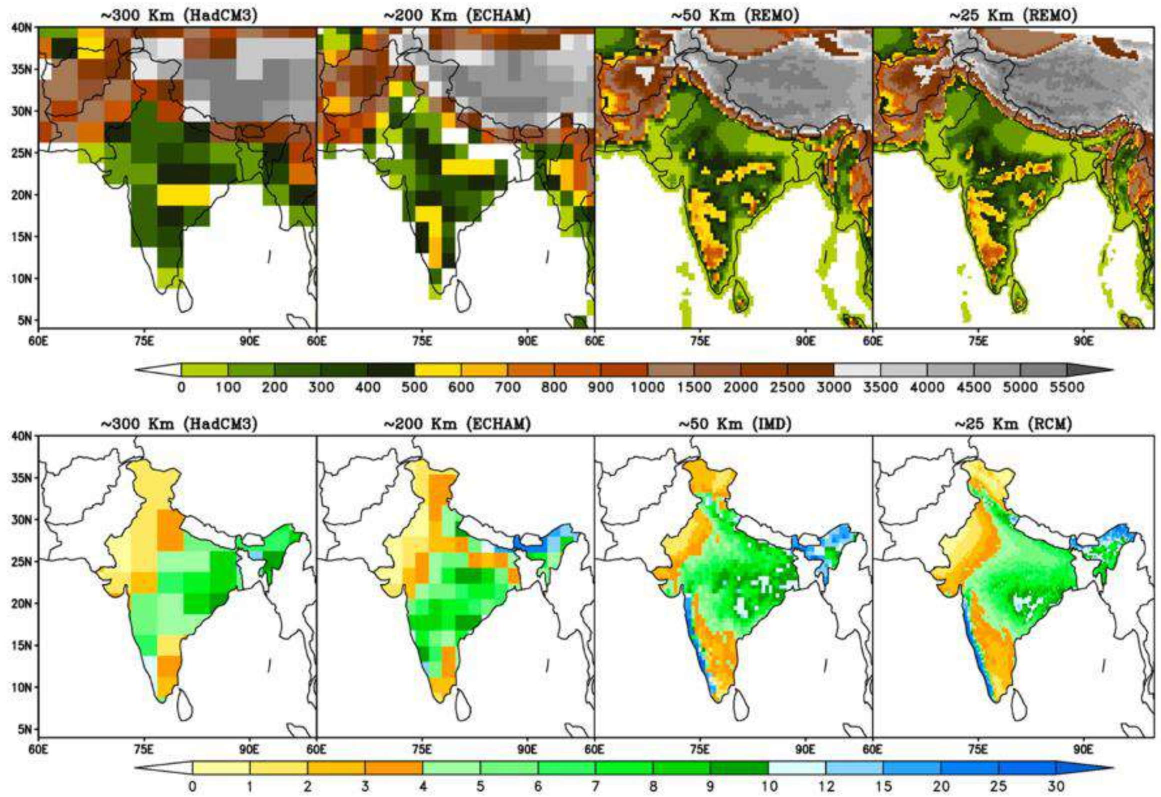


Figure 2.1 Upper panels show Climate model topography (in meters). The lower panels show the precipitation climatology (1970–1999, mm/d). IMD precipitation data is an observation, adapted from Kumar et al. 2013.

RESM has given a less intensive fix to the modelling community for simulating Indian Summer Monsoon precisely through regional customization of GCMs.

Addressing this pressing need for improved ISM simulations, a model from IIT Delhi, namely, India centric model (ICCM), has been developed by customizing region specific parameterization schemes of NCAR Community Earth System Model (Anand et al., 2018; Pathak et al., 2019; Namdev et al., 2022). ICCM shows improvements in the simulated seasonal and intra-seasonal ISM features along with improvements in long-standing biases such as early monsoon departure, monsoon winds, pattern and magnitude of precipitation, frequency of light precipitation and large-to-extreme precipitation etc. In addition, a further attempt is being made to dynamically downscale the ICCM products at the local/district scale of the country, which can be used in different suits of applications such as in hydrology, agriculture, disaster management etc.

Numerous studies have been undertaken to understand better the other important physical processes connected to ISM, including how ISM reacts to Antarctica's geography (Tewari et al., 2021a,b), consistent warming (Bhowmick et al., 2019), resolution of the model (Anand et al., 2019) and geo-engineering (Bhowmick et al., 2021). Additionally, substantial numerical modelling research has been done on how malaria risks in India's endemic regions respond to changing climatic conditions. (Singh et al., 2019; Parihar et al., 2022).

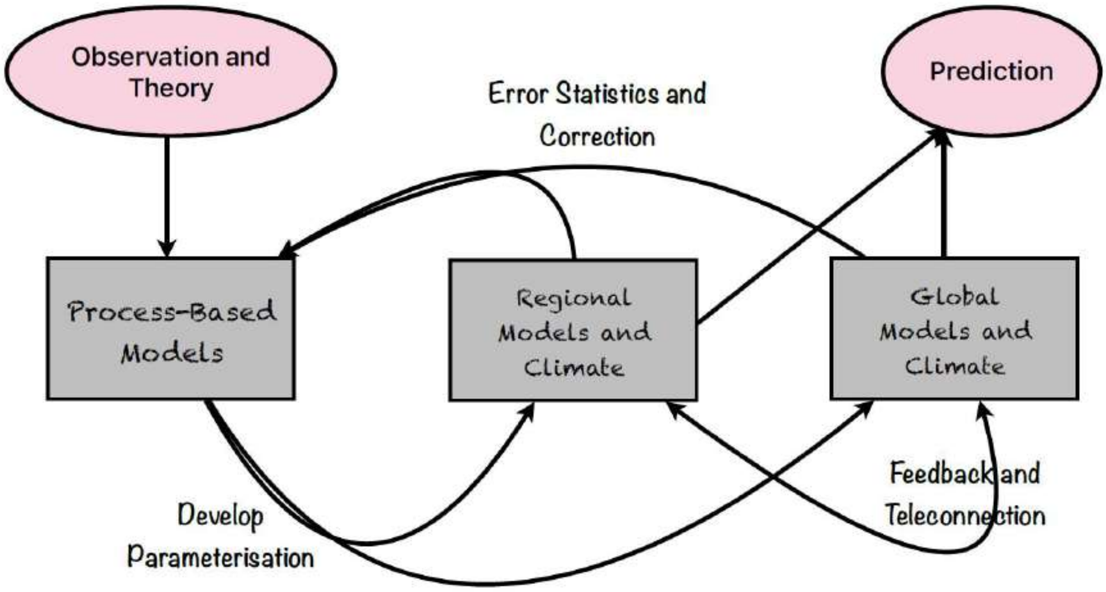


Figure 2.2: A conceptual view of the necessary components of climate modelling. It illustrates the importance of mutual interaction between different groups in order to use the observations and modelling in an adequate way to develop climate models along with improving our prediction and understanding of the climate.

In recent decades, RESMs with various components of earth systems, such as the land, atmosphere, oceans, biogeochemistry of marine, sea ice, hydrology etc., along with their complexities, have been developed and are used widely for a wide range of applications. (Hagedorn et al. 2000; Sein et al. 2014, 2015, 2020; Sevault et al. 2014; Wang et al. 2015b; Giorgi and Gutowski 2016; Ruti et al. 2016; Sitz et al. 2017; Reale et al. 2020).

Ruti et al. (2016) and Sevault et al. (2014) investigated the performance of a fully coupled model for the MED-CORDEX region and showed the robust performance of RESM. Reale et al. 2020 coupled the ocean component (MITgcm) with the atmosphere component (RegCM), studied the effectiveness of this fully coupled system and found a significant improvement in simulating the physical parameters of climate and marine biogeochemistry over the Mediterranean regions. Improvement in ocean and atmospheric field simulation is mainly brought about by the air-sea interaction.

Comparatively, lesser efforts have been put into developing a RESM for the Indian monsoon and exploring the various facets of ISM. Though a few investigations by (Kumar et al.,2013,2014a,2014b;

Samala et al. 2013; Di Sante et al. 2019; Mishra et al. 2020a,b; Kumar et at. 2022) showed a significant improvement in ISMR simulation, but some of the trials still exhibits a dry bias across central India.

For realistic simulations of weather or climate by the global or regional models, emphasis should be given to develop important components of climate models. These include cloud processes, land surface process, boundary layer processes, cryosphere processes, oceanic processes, and any other physical processes that can impact the climate. For example, the land surface is a crucial component of the climate that directly interacts with human activity. Yet, state-of-the-art land-surface models are not as advanced as, for example, the ocean models. One example is the lack of interaction between horizontal grids in a land-surface model inhibiting advection, which is an integral part of the dynamics in an atmosphere or ocean model. Another challenge is the interaction of land surface characteristics, mainly vegetation and, with the climate that can have adverse impact on Indian monsoon at different time scales (Chakraborty et al. 2022). Anthropogenic activities like irrigation is another important feather that should be well represented in climate models as it can have different impact on short- and long-term climate (Agrawal et al. 2019).

Similarly, Clouds play a significant role in the radiation and water budget of the earth. Cloud and convection are, however, one of the most challenging phenomena to simulate. This is because cloud-related processes range from micrometre (nucleation) to planetary (organisation) scales. We neither understand nor can represent/model these properties of clouds in state-of-the-art climate models.

Key Objectives

AI/ML in Climate Modelling

The earth system models, General Circulation Models and Regional Earth System Models are robust tools to predict the Earth system's response to anthropogenic climate change (Seneviratne and Hauser, 2020; Taylor et al., 2012). However, running a high-resolution RESM using forcing from several GCMs for all climate change scenarios for several hundred-year time scales is computationally expensive and time-consuming. The rapid development of Artificial Intelligence, Machine Learning (AIML) and Deep Learning (DL) techniques offer an excellent parallel approach to overcome these limitations. AIML techniques have shown their monopoly over various fields of science and technology. DL models are powerful because they can learn complex patterns across larger datasets, which can thereafter be utilized for making predictions. The AIML techniques are becoming competitive for predicting various time scales ranging from short (nowcasting) to long (multidecadal) timescales and spatial scales ranging from regional weather to the entire globe. Some drawbacks of AIML and DL applications in Earth system science are lack of interpretability, physical inconsistency, and lack of labelled data for training (Reichstein et al., 2019). Also, the representations and/or the nonlinear relationships learned by a neural network are hard to interpret and explain, and they are often considered 'black box' algorithms. The emerging domain of physics-informed machine learning (PIML) is a remedy for interpretability issues and models. In addition, AIML/PIML can be applicable for integrating research in the context of sustainable development. Due to substantial development in the existing observation and modelling capabilities, climate science is in the big data domain nowadays. The volume, velocity, and veracity of climate data produced daily have increased dramatically, and almost all weather and climate agencies take pride in keeping those enormous datasets publicly available; henceforth, it is high time to apply AIML and PIML techniques integrated with climate models to provide better prediction and projection skills than the existing methods.

In the context of application of AI/ML and DL in prediction and projections of ISMR, efforts are underway. Researchers at DST Centre of Excellence in Climate Modelling have extensively worked on this newly emerging field of research and found out that these techniques are performing reasonably well (Dash et al. 2018, Dash et al. 2019). For instance, Random Vector Functional Link Network (RVFL) turns out to be one of the promising approaches for seasonal prediction of ISMR (Dash et al. 2018). Moreover, application of AI-ML in understanding and predicting the short-term Flood-Drought events which categorically find importance in agricultural spheres, is also one among the multitude of applications of these techniques (Tyagi et al. 2022).

The primary objectives of modelling the climate should be twofold: (a) the models should provide a framework to understand the climate system, and (b) it should be possible to forecast and project climate characteristics at desired space and time scales accurately. With these grand goals in mind, we list the specific objectives below.

1. Develop earth system models: A realistic climate simulation is possible only when all its components are accurately incorporated into a model. This includes the atmosphere, the oceans, lands, the biosphere, the cryosphere, and anything else known to interact with the climate system. Such models are termed earth system models. India should develop earth system models of higher resolution (of the order of one-kilometre grid size) that can realistically capture the components like clouds and land surface heterogeneity.
2. Cloud and Convection Modelling: It is necessary to adequately represent clouds and convection processes in a model for reliable climate simulation. The thrust should be developing models of cloud microphysics and its interaction with large-scale climate. Emphasis can be given to building DNS models, LES models, cloud microphysics models, and finally, using their results to make a convection model for large-scale processes.
3. Land Surface Modelling: Emphasis should be given to developing interactive models that include agriculture, vegetation and soil properties as dynamically evolving. This will help better prediction and understanding of the climate.

ROADMAP

Short-term (2030):

1. Set up a national body of climate modellers (NBCM). The group can be constructed including researchers and educationalists from all parts of the climate system. It also should have representatives from educational institutes and national labs. The group can have different subgroups and levels. This body should chalk out a long-term earth system model development plan that is useful for forecasting at desired time scales and understanding the system.
2. Improve the weakest parts of a climate model: Convection parameterisation, cloud parameterisation, and land-surface parameterisation are some of the most erroneous features of a climate model. Researchers should focus on improving these parts in terms of their understanding, numerical representation, and simulation skill. These components can be achieved by standalone modelling and comparing their skill to some yardsticks.
3. Identify two or three atmosphere-ocean-land coupled models which can be modified continually to represent the climate better. It is beneficial to start with more than one model,

as no single model is perfect. At the same time, working with too many models may lead to untargeted research with inconclusive results.

4. Development of hybrid modelling (AIML + climate modelling) system to address climate extreme prediction at district levels for vulnerability-risk assessment and mitigation strategies.
5. Training professionals and generating human resource in climate modelling/regional climate modelling/climate change projection mitigation is required from academia and research organizations. Training workshops by institutions and universities in collaboration with scientific societies (e.g., Indian Meteorological Society) should be done regularly to harness young professionals in this interdisciplinary area of climate sciences.

Long-term (beyond 2030):

1. Provide thrust to research on paleoclimate.
2. Set up global climate models with about 1x1 km resolution. The kilometre-scale (k-scale) modelling is already a reality in many developed countries and India also should look forward for such an ambitious effort in the long-term future (Kendon et al., 2021).
3. Set up the model as a community model that can be accessed by all and has an essential support system.
4. Configure the climate model so it is easy to decouple its different components. Such a system would help improve various parts efficiently and provide an opportunity to simplify the complex climate system for better understanding.
5. Set up a research-application feedback system. Such a system of researchers and collaborators would be driven by a requirement (forecast, understanding) and development (model) loop. For example, model developers would require specific observations to ‘model’ and ‘standardize’ some components of the climate system. This could include suggesting/planning new observations/field campaigns based on requirements. Such a system is mostly missing in the country so far.
6. Development of climate extreme prediction systems based on the following integrated Artificial Intelligence and Machine Learning (AIML) and climate modelling approach (i) Downscaling and Causal discovery (xAI), (ii) Emulators for complex physical processes, e.g., urban dynamics, cloud resolving models, (iii) Hybrid modelling setup, Physics Informed Machine Learning (PIML) and High-resolution climate models, (iv) Climate extremes prediction using the fusion of AIML-ESM/RESM simulations.

REFERENCES

Agrawal, S., Arindam Chakraborty, N. Karmakar, Simon Moulds, Ana Mijic and Wouter Buytaert., 2019. Effects of winter and summer-time irrigation over Gangetic Plain on the mean and intra-seasonal variability of Indian summer monsoon, Climate Dynamics, 53: 3147. https://doi.org/10.1007/s00382-019-04691-7

Anand, A., Bhowmick, M., Mishra, S.K., Sahany, S. and Telukuntla, C.V.R., 2019. Response of Indian monsoon to increase of resolution in NCAR-CAM5. Atmospheric Research, 221, pp.12-26.

Anand, A., Mishra, S.K., Sahany, S., Bhowmick, M., Rawat, J.S. and Dash, S.K., 2018. Indian summer monsoon simulations: Usefulness of increasing horizontal resolution, manual tuning, and semi-automatic tuning in reducing present-day model biases. Scientific reports, 8(1), pp.1-14.

Bhaskaran B, Jones RG, Murphy JM, Noguer M., 1996. Simulations of the Indian summer monsoon using a nested regional climate model: domain size experiments. Clim Dyn;12:573–87.

Bhowmick, M., Mishra, S.K., Kravitz, B. et al., 2021. Response of the Indian summer monsoon to global warming, solar geoengineering and its termination. Sci Rep 11, 9791. https://doi.org/10.1038/s41598-021-89249-6

Bhowmick, M., Sahany, S. and Mishra, S.K., 2019. Projected precipitation changes over the south Asian region for every 0.5 C increase in global warming. Environmental Research Letters, 14(5), p.054005.

Chakraborty, A., JB Samuel, and A. Paleri.,2022. Role of land-surface vegetation in the march of Indian monsoon onset isochrones in a coupled models, *Quarterly Journal of the Royal Meteorological Society*, DOI: https://doi.org/10.1002/qj.4398

Das SK, Shekhar MS, Singh GP., 2006. Simulation of Indian Summer monsoon circulation and rainfall using RegCM3. Theor Appl Climatol;86:161–72.

Dash SK, Mishra SK, Pattnayak KC, Mamgain A, Mariotti L, Coppola E, Giorgi F, Giuliani G., 2015a. Projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century. Theoretical and Applied Climatology.;122(3):581-93.

Dash SK, Pattnayak KC, Panda SK, Vaddi D, Mamgain A.,2015b. Impact of domain size on the simulation of Indian summer monsoon in RegCM4 using mixed convection scheme and driven by HadGEM2. Climate dynamics.44(3):961-75.

Dash, Y., Mishra, S.K. and Panigrahi, B.K., 2019. Predictability assessment of northeast monsoon rainfall in India using sea surface temperature anomaly through statistical and machine learning techniques. Environmetrics, 30(4), p.e2533.

Dash, Y., Mishra, S.K., Sahany, S. and Panigrahi, B.K., 2018. Indian summer monsoon rainfall prediction: a comparison of iterative and non-iterative approaches. Applied Soft Computing, 70, pp.1122-1134.

Di Sante F, Coppola E, Farneti R, Giorgi F., 2019. Indian Summer Monsoon as simulated by the regional earth system model RegCM-ES: the role of local air–sea interaction. Climate dynamics. Jul;53(1):759-78.

Dimri AP, Yasunari T, Wiltshire A, Kumar P, Mathison C, Ridley J, Jacob D.,2013. Application of regional climate models to the Indian winter monsoon over the western Himalayas. Sci Total Environ ;468–469(Suppl.):S36–47.

Dobler A, Ahrens B., 2010. Analysis of the Indian summer monsoon system in the regional climate model COSMO-CLM. J Geophys Res;115:D16101. http://dx.doi.org/ 10.1029/2009JD013497

Fu X, Wang B, Waliser DE, Tao L.,2007. Impact of atmosphere-ocean coupling on the predictability of monsoon intraseasonal oscilla- tions. J Atmos Sci 64:157–174. https://doi.org/10.1175/JAS38 30.1

Giorgi F, Gao XJ.,2018. Regional earth system modeling: review and future directions. Atmos Ocean Sci Lett 11:189–197. https://doi. org/10.1080/16742834.2018.1452520

Giorgi F, Gutowski WJ., 2016. Coordinated experiments for projections of regional climate change. Curr Clim Chang Reports 2:202–210.

Giorgi F, Mearns LO., 2002. Calculation of average, uncertainty range, and reliability of region- al climate changes from AOGCM simulations via the reliability ensemble averaging (REA) method. J Climate;15:1141–58.

Giorgi F., 2006. Regional climate modeling: status and perspectives. J Phys IV France;139: 101–18. http://dx.doi.org/10.1051/jp4:2006139008

Giorgi F., 2019 . Thirty years of regional climate modeling: where are we and where are we going next?. Journal of Geophysical Research: Atmospheres. 16;124(11):5696-723.

Goswami, B. N.,1998. Interannual variations of Indian summer monsoon in a GCM: External conditions versus internal feedbacks. Journal of Climate, 11(4), 501-522.

Hagedorn R, Lehmann A, Jacob D.,2000. A coupled high resolution atmosphere-ocean model for the BALTEX region. Meteorol Zeitschrift 9:7–20. https://doi.org/10.1127/metz/9/2000/7

Hu, X., Taylor, P. C., Cai, M., Yang, S., Deng, Y., & Sejas, S.,2017. Inter-model warming projection spread: inherited traits from control climate diversity. Scientific reports, 7(1), 4300.

Jacob D, Podzum R., 1997. Sensitivity studies with the Regional Climate Model REMO. Meteorol Atmos Phys;l(63):119–29.

Jacob D,. 2009. Regional climate models: linking global climate change to local impacts. The Springer encyclopedia of complexity and systems science, pp. 7591-7602.

Jacob D., 2001. A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. Meteorol Atmos Phys;77:61–73.

Jain, S., Salunke, P., Mishra, S.K. and Sahany, S., 2019. Performance of CMIP5 models in the simulation of Indian summer monsoon. Theoretical and Applied Climatology, 137(1), pp. 1429-1447.

Ji Y, Vernekar AD., 1997. Simulation of the Asian summer monsoons of 1987 and 1988 with a regional model nested in a global GCM. J Climate;10:1965–79.

Kendon, E. J., Prein, A. F., Senior, C. A., & Stirling, A., 2021. Challenges and outlook for convection-permitting climate modelling. Philosophical Transactions of the Royal Society A, 379(2195), 20190547.

Kodra, E., Ghosh, S., & Ganguly, A. R.,2012. Evaluation of global climate models for Indian monsoon climatology. Environmental Research Letters, 7(1), 014012.

Kumar P, Podzun R, Hagemann S, Jacob D.,2014c. Impact of modified soil thermal characteristic on the simulated monsoon climate over south Asia. J Earth Syst Sci 123:151–160. https://doi.org/ 10.1007/s12040-013-0381-0

Kumar, P., Mishra, A. K., Dubey, A. K., Javed, A., Saharwardi, M., Kumari, A., ... & Sein, D. V.,2022. Regional earth system modelling framework for CORDEX-SA: an integrated model assessment for Indian summer monsoon rainfall. *Climate Dynamics*, 1-20.

Kumar, P., Sein, D., Cabos, W., Jacob, D., 15-19 December., 2014a. Improved precipitation extremes and climatology in a regional coupled model simulation over CORDEX South Asia domain. AGU Fall Meeting. https://agu.confex.com/agu/fm14/meetingapp.cgi/Paper/16921

Kumar, P., Sein, D., Cabos, W., Jacob, D., 2014b. Improvement of simulated monsoon precipitation over South Asia with a regionally coupled model ROM. In: B¨arring, L.,Reckermann, M., Rockel, B., Rummukain, M. (Eds.), 3rd International Lund Regional-Scale Climate Modelling Workshop 21st Century Challenges in Regional Climate Modelling: Workshop proceedings, Lund, Sweden.

Kumar, P., Wiltshire, A., Mathison, C., Asharaf, S., Ahrens, B., Lucas-Picher, P., Christensen, J.H., Gobiet, A., Saeed, F., Hagemann, S., Jacob, D., 2013. Downscaled climate change projections with uncertainty assessment over India using a high resolution multi-model approach. Sci. Total Environ. 468–469, S18–S30. https://doi.org/10.1016/j.scitotenv.2013.01.051

Levine RC, Martin GM.,2018. On the climate model simulation of Indian monsoon low pressure systems and the effect of remote disturbances and systematic biases. Clim Dyn 50:4721–4743. https://doi.org/10.1007/s00382-017-3900-x

Li Y, Han W, Zhang L, Ravichandran .,2018. The Indian summer monsoon intraseasonal oscillations in CFSv2 forecasts: biases and importance of improving air-sea interaction processes. J Clim 31:5351–5370. https://doi.org/10.1175/JCLI-D-17

Lucas-Picher P, Christensen JH, Saeed F, Kumar P, Asharaf S, Ahrens B, et al., 2011. Can regional climate models represent the Indian monsoon? J Hydrometeoroly;12:849–68. http://dx.doi.org/10.1175/2011JHM1327.1

Mathison C, Wiltshire A, Kumar P, Dimri AP, Ridley J, Jacob D, et al., 2013. Regional Projections of South Asian Climate for Adaptation studies. Sci Total Environ;468–469(Suppl.): S4–7.

Meehl GA, Covey C, Delworth T et al.,2007. The WCRP CMIP3 multimodel dataset: A new era in climatic change research. Bull Am Meteorol Soc 88:1383–1394. https://doi.org/10.1175/ BAMS-88-9-1383

Mishra AK, Dubey AK.,2021. Sensitivity of convective parameteriza- tion schemes in regional climate model: precipitation extremes over India. Theoret Appl Climatol. https://doi.org/10.1007/ s00704-021-03714-w

Mishra AK, Dwivedi S, Das S.,2020a. Role of Arabian Sea warming on the Indian summer monsoon rainfall in a regional climate model. Int J Climatol 40:2226–2238. https://doi.org/10.1002/ joc.6328

Mishra AK, Dwivedi S, Di Sante F, Coppola E.,2020b. Thermody- namical properties associated with the Indian summer monsoon rainfall using a regional climate model. Theoret Appl Climatol 141:587–599. https://doi.org/10.1007/s00704-020-03237-w

Mishra AK, Dwivedi S, Di Sante F.,2021a. Performance of the RegCM-MITgcm coupled regional model in simulating the Indian summer monsoon rainfall. Pure Appl Geophys. https:// doi.org/10.1007/s00024-020-02648-0

Mishra AK, Kumar P, Dubey AK et al.,2021b. Impact of horizontal resolution on monsoon precipitation for CORDEX-South Asia: a regional earth system model assessment. Atmos Res 259:105681. https://doi.org/10.1016/j.atmosres.2021.105681

Mishra, S. K., Anand, A., Fasullo, J., & Bhagat, S., 2018. Importance of the resolution of surface topography in Indian monsoon simulation. Journal of Climate, 31(12), pp. 4879-4898.

Mishra, S. K., Sahany, S., Salunke, P., Kang, I. S., & Jain, S., 2018. Fidelity of CMIP5 multi-model mean in assessing Indian monsoon simulations. npj Climate and Atmospheric Science, 1(1), pp. 1-8.

Misra V, Mishra A, Bhardwaj A.,2018. Simulation of the intraseasonal variations of the Indian summer monsoon in a regional coupled ocean-atmosphere model. J Clim 31:3167–3185. https://doi.org/ 10.1175/JCLI-D-17-0434.1

Moors EJ, Biemans H, Groot A, Terwissch van Scheltinga C, Siderius C, Stoffel M, et al., 2012. Adapting to climate change: reducing water-related risks in Europe. Environ Sci Policy;14(7):758–69. http://dx.doi.org/10.1016/j.envsci.2011.03.005.

Namdev, P., Sharan, M. and Mishra, S.K.,2022. Impact of the Similarity Functions of Surface Layer Parameterization in a Climate Model over the Indian Region. Quarterly Journal of the Royal Meteorological Society.

Parihar, R.S., Bal, P.K., Saini, A., Mishra, S.K. and Thapliyal, A., 2022. Potential future malaria transmission in Odisha due to climate change. Scientific Reports, 12(1), pp.1-13.

Pathak, R., Sahany, S., Mishra, S.K. and Dash, S.K., 2019. Precipitation biases in CMIP5 models over the south Asian region. Scientific reports, 9(1), pp.1-13.

Pattnayak KC, Panda SK, Saraswat V, Dash SK.,2018. Assess- ment of two versions of regional climate model in simulat- ing the Indian Summer Monsoon over South Asia CORDEX domain. Clim Dyn 50:3049–3061. https://doi.org/10.1007/ s00382-017-3792-9

Rajeevan M, Nanjundiah RS., 2009. Coupled model simulations of twentieth century climate of the Indian summer monsoon. In: Mukunda N, editor. Current trends in science: platinum jubilee special. Indian Academy of Sciences; p. 537–68.

Ratnam JV, Giorgi F, Kaginalkar A, Cozzini S.,2009.Simulation of the Indian monsoon using the RegCM3-ROMS regional cou- pled model. Clim Dyn 33:119–139. https://doi.org/10.1007/ s00382-008-0433-3

Ratnam JV, Kumar KK., 2005. Sensitivity of the simulated Monsoons of 1987 and 1988 to con- vective Parameterization Scheme in MM5. J Climate;18:2724–43.

Reale M, Giorgi F, Solidoro C et al.,2020. The regional earth sys- tem model RegCM-ES: evaluation of the mediterranean climate and marine biogeochemistry. J Adv Model Earth Syst 12:1812. https://doi.org/10.1029/2019MS001812

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., Prabhat, 2019. Deep learning and process understanding for data-driven Earth system science. Nature 566, 195–204. https://doi.org/10.1038/s41586-019-0912-1

Ruti PM, Somot S, Giorgi F et al.,2016. Med-CORDEX initiative for Mediterranean climate studies. Bull Am Meteorol Soc 97:1187– 1208. https://doi.org/10.1175/BAMS-D-14-00176.1

Sabeerali CT, Ramu Dandi A, Dhakate A et al.,2013. Simulation of boreal summer intraseasonal oscillations in the latest CMIP5 coupled GCMs. J Geophys Res Atmos 118:4401–4420. https:// doi.org/10.1002/jgrd.50403

Samala BK, C N, Banerjee S, et al.,2013. Study of the Indian summer monsoon using WRF-ROMS regional coupled model simula- tions. Atmos Sci Lett 14:20–27. https://doi.org/10.1002/asl2.409

Sein DV, Gröger M, Cabos W et al.,2020. Regionally coupled atmos- phere-ocean-marine biogeochemistry model ROM: 2. Studying the climate change signal in the North Atlantic and Europe. J Adv Model Earth Syst. https://doi.org/10.1029/2019MS001646

Sein DV, Koldunov NV, Pinto JG, Cabos W.,2014. Sensitivity of sim- ulated regional Arctic climate to the choice of coupled model domain. Dyn Meteorol Oceanogr 66:23966. https://doi.org/10. 3402/tellusa.v66.23966

Sein DV, Mikolajewicz U, Gröger M et al.,2015. Regionally coupled atmosphere-ocean-sea ice-marine biogeochemistry model ROM: 1. Description and validation. J Adv Model Earth Syst 7:268– 304. https://doi.org/10.1002/2014MS000357

Seneviratne, S.I., Hauser, M., 2020. Regional Climate Sensitivity of Climate Extremes in CMIP6 Versus CMIP5 Multimodel Ensembles. Earths Future 8. https://doi.org/10.1029/2019EF001474

Sevault F, Somot S, Alias A et al.,2014. A fully coupled Mediter- ranean regional climate system model: design and evaluation of the ocean component for the 1980–2012 period. Tellus A Dyn Meteorol Oceanogr 66:23967. https://doi.org/10.3402/tellusa. v66.23967

Sharmila S, Joseph S, Sahai AK et al.,2015. Future projection of Indian summer monsoon variability under climate change scenario: an assessment from CMIP5 climate models. Glob Planet Change 124:62–78. https://doi.org/10.1016/j.gloplacha.2014.11.004

Singh Parihar, R., Bal, P.K., Kumar, V., Mishra, S.K., Sahany, S., Salunke, P., Dash, S.K. and Dhiman, R.C., 2019. Numerical modeling of the dynamics of malaria transmission in a highly endemic region of India. Scientific Reports, 9(1), pp.1-9.

Sitz LE, Di Sante F, Farneti R et al.,2017. Description and evaluation of the Earth System Regional Climate Model (Reg CM-ES). J Adv Model Earth Syst 9:1863–1886. https://doi.org/10.1002/2017MS000933

Srivastava, G., Chakraborty, A. & Nanjundiah, R.S.,2019. Multidecadal see-saw of the impact of ENSO on Indian and West African summer monsoon rainfall. *Climate Dynamics* **52**, 6633–6649. https://doi.org/10.1007/s00382-018-4535-2

Stockhause M, Lautenschlager M.,2017. CMIP6 data citation of evolving data. Data Sci J 16:1–13. https://doi.org/10.5334/ dsj-2017-030

Stowasser M, Annamalai H, Hafner J.,2009. Response of the South Asian summer monsoon to global warming: mean and synoptic systems. J Clim 22:1014–1036. https://doi.org/10.1175/2008J CLI2218.1

Swapna, P., Krishnan, R., Sandeep, N., Prajeesh, A. G., Ayantika, D. C., Manmeet, S., & Vellore, R.,2018. Long-term climate simulations using the IITM Earth system model (IITM-ESMv2) with focus on the south Asian monsoon. Journal of Advances in Modelling Earth Systems, **10**(5) , 1127– 1149. https://doi.org/10.1029/2017MS001262

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An Overview of CMIP5 and the Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Tewari, K., Mishra, S. K., Fasullo, J., & Dewan, A., 2021a. Impact of the Antarctic topography on meridional energy transport and its consequential effect in the monsoon circulation. Quarterly Journal of the Royal Meteorological Society, 147(739), 3286-3296.

Tewari, K., Mishra, S.K., Dewan, A., Anand, A. and Kang, I.S., 2021b. Response of the Atmosphere to Orographic Forcings: Insight from Idealized Simulations. Journal of the Atmospheric Sciences, 78(9), pp.2691-2708.

Turner AG, Annamalai H.,2012. Climate change and the South Asian summer monsoon. Nat Clim Change 2:587–595

Tyagi, S., Zhang, X., Saraswat, D., Sahany, S., Mishra, S.K. and Niyogi, D., 2022. Flash Drought: Review of Concept, Prediction and the Potential for Machine Learning, Deep Learning Methods. Earth's Future, 10(11), p.e2022EF002723.

Wang S, Dieterich C, Döscher R et al.,2015. Development and evalu- ation of a new regional coupled atmosphere–ocean model in the North Sea and Baltic Sea. Tellus A Dyn Meteorol Oceanogr 67:24284. https://doi.org/10.3402/tellusa.v67.24284

Wu Y, Simpson IR, Seager R.,2019. intermodel spread in the northern hemisphere stratospheric polar vortex response to climate change in the CMIP5 models. Geophys Res Lett 46:13290–13298. https://doi.org/10.1029/2019GL085545

Xue P, Malanotte-Rizzoli P, Wei J, Eltahir EAB.,2020. Coupled ocean- atmosphere modeling over the maritime continent: a review. J Geophys Res Ocean. https://doi.org/10.1029/2019JC014978

CHAPTER 3: OCEANIC SCIENCES

Abhisek Chatterjee, Srinivasa Kumar T, Francis P A, Aneesh Lotliker and S A Sannasiraj

Coordinating Lead Author
Dr. Srinivasa Kumar Tummala, INCOIS Hyderabad

Lead Authors
Dr. Abhisek Chatterjee, INCOIS Hyderabad
Dr. Francis P A, INCOIS Hyderabad
Dr. Aneesh Lotliker, INCOIS Hyderabad
Prof. S A Sannasiraj, IIT Madras

BACKGROUND

It is now well accepted that the ongoing climate change will have irreversible and far-fetching effects on all the components of the Earth System. Ocean covers 71% of the earth's surface containing 97% of the earth's water and thus plays a central role in regulating the Earth's hydrological cycle and climate by the uptake and redistribution of anthropogenic heat and carbon dioxide. Owing to the increase in the concentration of greenhouse gasses (GHGs), especially anthropogenic CO_2, Earth's climate is changing continuously, which leads to the melting of ice in the polar region and internal expansion of oceans due to thermosteric effects. These changes are resulting in a rise in sea level and increase in the frequency and intensity of extreme events such as marine heatwaves, spells of heavy rain, droughts, forest fires, very severe tropical cyclones, higher rate of erosion affecting beaches, deltas and islands, etc. All coastal zones across the globe and the 37 % of population inhabiting these zones and relying on marine resources for their livelihood are expected to bear the brunt of these climate-induced extreme changes. Furthermore, it has been widely recognized that climate change can have far-reaching consequences on the coastal surface and groundwater (e.g., saltwater ingression), health of coastal ecosystems (e.g. wetlands and biodiversity loss), marine biological communities and commercial species (IPCC, 2021).

India is the seventh largest country in the world with a geographical area of 3,287,263 square kilometres, amounting to about 2.4% of the global land area. Also, India has the second largest human population of 1.4 billion and is expected to surpass China this year (UN World Population Prospects 2022). A large portion of this population is living along its 7500 km long coastline and thereby, vulnerable to the

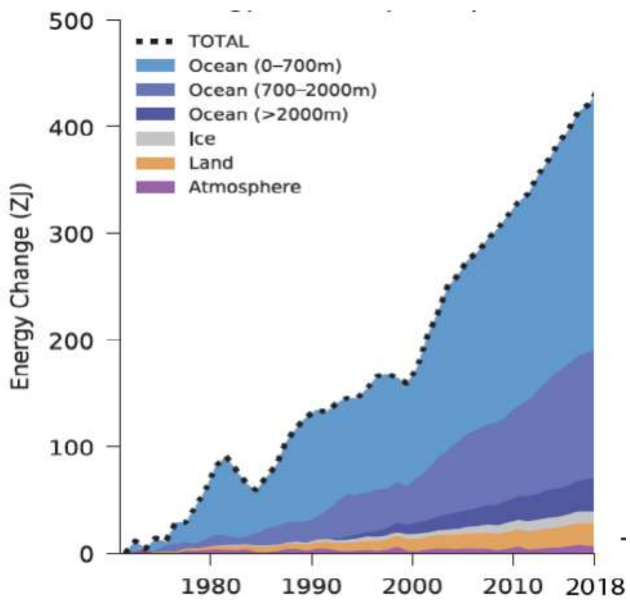


Figure 3.1: Contribution of various components in the net cumulative change in the Earth's energy budget (ZJ= 10^{21} J). (Adopted from IPCC 2021: Physical Science Basis)

diverse climatic extremes. Further, India's economy heavily relies on its vast Exclusive Economic Zone (EEZ) of about 2,305,143 square kilometres consisting of large marine resources including biotic (e.g., fisheries), abiotic (minerals) and commercial (navigation and transport). Hence, assessing the impact of climate change on our marine environment and associated economy are particularly relevant in building adaptation and mitigation policies to meet energy and food security, to achieve the Sustainable Development Goals, and to the success of India's Blue Economy initiatives.

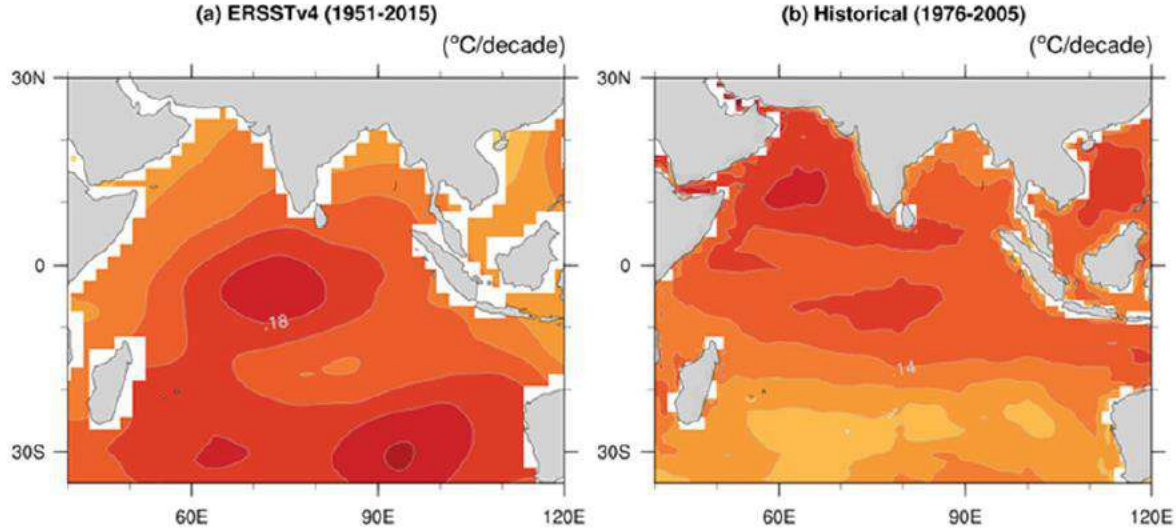


Figure 3.2: SST trend (°C/decade) from: a observed Extended Reconstructed SST trend (°C/decade) from ERSSTv4 during 1951–2015, b CMIP5 historical simulations for 1976–2005. Adopted from MoES report on "Assessment of Climate Change over the Indian Region".

It has been estimated that the global oceans have stored about 91% of the total energy gained by the earth system during 1971-2018, which amounts to 396 [285.7−506.2]×10^{21}J, due to the high specific heat capacity of water compared to the other components of the Earth System (IPCC 2021: Physical Science Basis) (Figure 3.1). This leads to a rapid increase in the ocean surface and subsurface temperature. On average, ocean surface temperature has increased by 0.88 [0.68−1.01]°C relative to the 1850-1900 period. The tropical Indian Ocean has experienced basin-wide warming with an average estimated rise of about 1°C relative to 1951, at a rate of 0.15°C per decade (MoES Climate Change report, 2020; Roxy et al., 2014). As a result, marine heatwaves, representing periods of anomalously high near-surface temperature, have become more intense and prolonged and their frequency of occurrences have doubled since the 1980's (Frölicher et al., 2018). In the Indian Ocean, the Arabian Sea witnessed maximum increase in the heatwave events at a rate of ~1.5-2 events per decade (an increase of ~20 heatwave days per decade) (Chatterjee et al., 2022; Saranya et al., 2022) followed by the northern Bay of Bengal (Saranya et al., 2022). These heatwave events not only affect marine ecosystems adversely through coral bleaching (Hughes et al., 2017; Mohanty et al., 2013 & 2017) and thus impacting habitat of the economically important fish stock, but are also shown to be responsible for increased cyclonic activities in the Bay of Bengal (Rathore et al., 2022) and in the Arabian Sea (Chatterjee et al., 2022).

According to the 6th assessment report of IPCC (Intergovernmental Panel on Climate Change), the recent reported global mean sea level rise of ~3.7 mm/year during 2006-2018 is unprecedented over the last century. Recent advancement in the understanding of the global mean sea level budget suggests that the observed sea level change over the 20th century is primarily contributed by glacial melt (52%), Greenland ice-sheet mass loss (29%) and the effect of thermal expansion (32%). The land-water storage contributed negatively (-19%) to the global mean sea level rise through natural and anthropogenic reservoir impoundment and groundwater depletion (Cáceres et al., 2020; Frederikse et al., 2020b). On average, the Indian Ocean sea level rise is comparable to the global mean i.e. around 3.3 mm/year in the recent decade (1993-2015) (Unnikrishnan and Shankar 2007; MoES climate change report) and is dominated by the ocean thermosteric effect (Srinivasu et al., 2017; Swapna et al., 2017). As per a recent estimate based on best-selected CMIP6 models for the Indian Ocean, the projected change in the dynamic sea level at the end of 21st-century relative to the historical period (1994-2014) is expected to be in the range of 35-40 cm under the SSP5-8.5 scenario (Sajidh and Chatterjee, 2023).

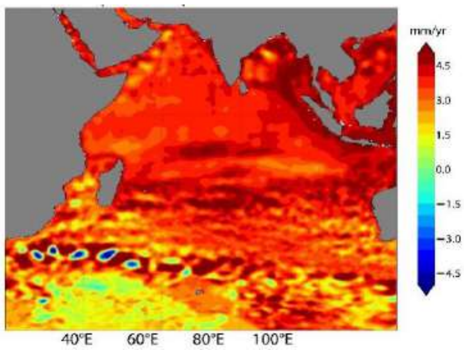


Figure 3.3: Sea level trend (mm/yr) based on gridded altimeter record.

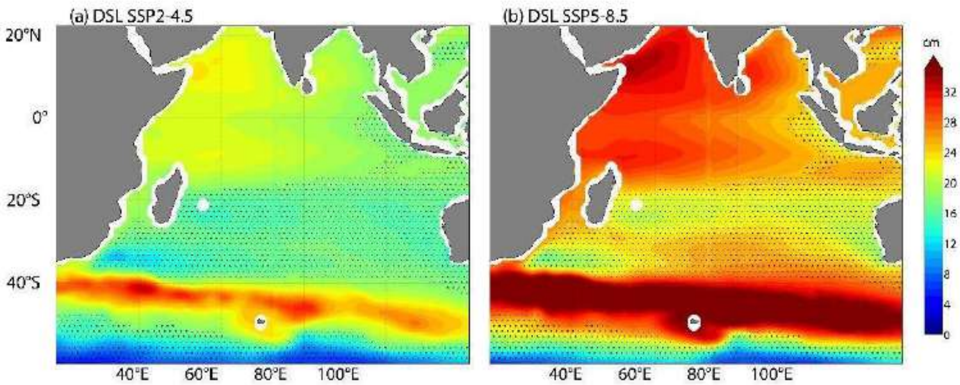


Figure 3.4: Dynamic Sea Level under Projected Climate Scenario

The impacts of sea level rise will be further amplified due to an increase in severe tropical cyclone frequency and intensity (Webster et al., 2005; Emanuel, 2005; Mohapatra et al. 2015). The translational speeds of tropical cyclones are also undergoing rapid changes over the north Indian Ocean, increasing over the Bay of Bengal while decreasing over the Arabian Sea during 1961–2010 (Geetha and Balachandran, 2014) consistent with the global ocean warming trend. Increase in the storm surges due to intense tropical cyclones can worsen the coastal flooding situation as it pushes the waves inshore, particularly if they occur during high tide. Additionally, the change in the wind-generated waves, in combination with the storm surges, is expected to cause more severe flooding in the coastal regions (Storlazzi et al. 2018). Such increase in coastal flooding due to the combined effect of sea level rise will lead to increased erosion, destruction of drainage systems and regional water management issues such as saltwater intrusion into the aquifers and local water supply wells. Such impacts are already noticeable in the low-lying areas of Sundarban estuaries, Andaman and Nicobar and Lakshadweep islands. The increase in sea level can also adversely affect the efficiency of power plants installed near shorelines as most of them use seawater for cooling purposes and increased coastal flooding can affect their operations particularly during storm surges and extreme wave conditions (Bierkandt et al 2015).

The impact on the coastal economy will further exacerbate due to the degradation of the marine biodiversity and water quality driven by depletion of oxygen, increase in temperature/stratification (Bindoff et al., 2019) and acidification (Doney et al., 2009). While the anthropogenic increase in atmospheric CO_2 is one of the most critical problems for marine ecology, other regional factors like intensive use of fertilizers, over-exploitation of fish stocks, increasing aquaculture productions and invasive species also equally influence the coastal ecosystem (Halpern et al., 2008). Globally coastal ecosystems are degrading rapidly with irreversible loss in 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrass (Jackson, 2010). There is also evidence that the planktonic system in the Northern Arabian Sea has shifted over the last decade, from diatom-dominated communities to progressively more prevalent blooms of mixotrophic, green variant of the dinoflagellate Noctiluca (Gomes et al., 2014). It is also possible that climatic warming of surface waters has contributed to increasing green Noctiluca abundance (Kumar et al., 2009). This transition potentially has major ramifications for secondary and tertiary production including fisheries. In addition, it is also evident that the bloom originating from north-western Arabian Sea spreads towards eastern Arabian Sea and may have significant impact in the Indian coastal waters (Lotliker et al., 2020). Therefore, understanding the mechanisms underlying this change are important not only for forecasting future conditions, but because these changes might signal planktonic shifts in coastal ecosystem. The recent IPCC (IPCC WGII, 2021) report suggests that near-term climate change conditions are projected to deteriorate further and beyond a level to which most of the Atlantic and Indian Ocean coral reefs will translate into net erosion and degradation, and most blue carbon systems such as mangrove forests, seagrass meadows and tidal marshes will get eroded due to sea level rise. Most importantly, the Indian coastal ecosystem is no exception from the global scenario. Local factors such as changes in land use, particularly agricultural activities, urbanization and industrialization, construction of new ports along the Indian coasts, etc. make coastal ecology vulnerable to anthropogenic perturbations. For example, the Kochi backwaters/estuary has transformed from an intense autotrophic system four decades ago to an intense heterotrophic system now due to increased human pressure from urban and industrial activities (Gupta et al., 2009).

In addition to anthropogenic changes, natural climate variabilities such as coupled dynamics of the Indo-Pacific warm pool, El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) contribute to exacerbating the extreme events in interannual and decadal timescale. For example, El Niño conditions caused basin-wide warming in the Indian Ocean leading to one of the prolonged observed heatwave events in the recent past, triggering extensive bleaching of corals across the global oceans. Moreover, while El Niño may also cause drought and forest fires in the Indian subcontinents, a positive phase of IOD tends to enhance the Indian monsoon. However, in the ongoing global warming, the coupled feedback mechanisms between the different facets of Earth systems are also changing. The weakening relationship between ENSO and the Indian monsoon (Kumar et al., 1999), increased frequency of IOD (Abram et al., 2020), and weakening of the southern Indian Ocean Dipole (Zhang et al., 2022) are few responses to such changes in coupled feedback paradigm shifts.

Inter-basin connections and their interannual to decadal variabilities contribute to the transport of heat and carbon exchange between the ocean and atmosphere, and to mechanisms of their redistribution across the globe. For example, the warming of the Indian Ocean in recent decades is attributed to the decadal changes in heat transport from the Pacific into the Indian Ocean upper/subsurface water column (Lee et al., 2015; Nieves et al., 2015). On the other hand, the Southern Ocean, a region undergoing a very deep-reaching warming of up to 2000 m water column, potentially redistributing heat to the tropical south Indian Ocean through meridional overturning circulation (Yang et al., 2020). A recent study by Gadgil et al. (2023) showed that the variation of SST in the eastern Arabian Sea affects the ENSO-Monsoon relationship, particularly during the La Nina events. Changes in the monsoon circulation (Sandeep and Ajayamohan, 2015), warming of the northern Arabian Sea and its link to the increased frequency of extreme rainfall events over the Indian subcontinent (Li et al., 2021) are also a few consequences of global warming/climate change in the Indian Ocean region. Therefore, a holistic understanding of these internal climate variabilities and their impacts on the extremes is important for improving near-term predictability and reducing longer-term projection uncertainties.

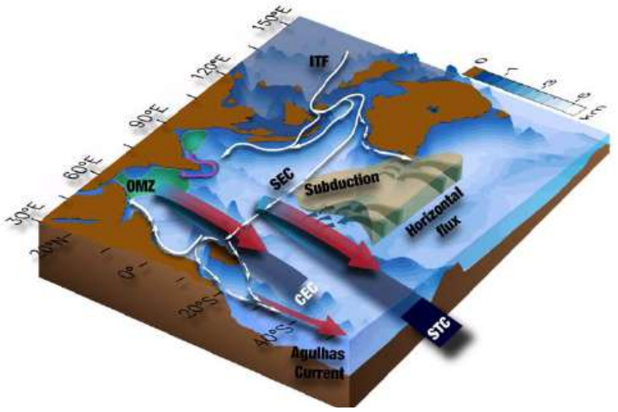


Figure 3.5: Oceanic inter-basin connections and the over-turning circulation responsible for transporting heat and carbon across the basin.

In the following sections we try to highlight the current status, knowledge gaps and future work to enhance our understanding of the ocean climate nexus:

Current Status

Ocean Observing Networks: Over the past few decades, India has built a strong partnership with global initiatives such as the Global Ocean Observing System (GOOS) in maintaining an effective network of ocean observations like Argo, XBT/XCTD transacts, Moored Ocean Observation Network, and support to the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) programme of NOAA/PMEL under the INDO-US collaboration, etc. Additionally, the Ministry of Earth Sciences (MoES) maintains an array of coastal observation networks such as tide gauges, coastal ADCP moorings, Coastal Ocean Dynamics Application Radars (CODARs), wave rider buoys, etc. As part of its coastal monitoring programme, buoy-based autonomous water quality observatories in Indian coastal waters along India's west and east coast have been taken up. Further, recent deployments of advanced autonomous underwater vehicles like deep ocean gliders, deep argo and wave drifters to continuously monitor climate indicators provide a much-needed technological edge in ocean climate observations. India also has a very strong satellite ocean remote sensing programme which received a boost with the recent launch of Oceansat-3 (EOS-6). Data from all the in-situ and remote sensing ocean observations are efficiently and effectively used for enhancing our understanding of the oceanic processes, assimilating into ocean models and also validation of model products.

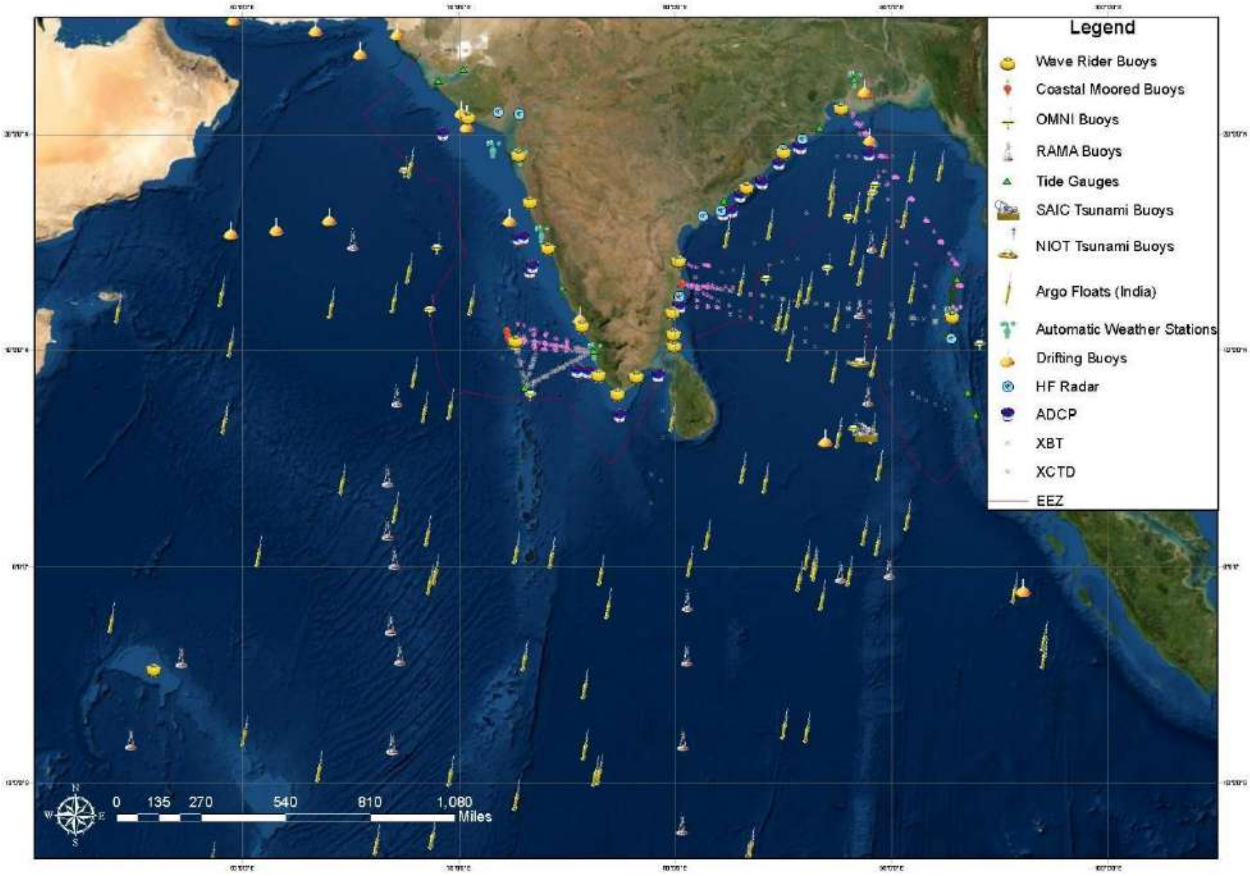


Figure 3.6: Existing active observation networks of the Indian Ocean.

Process Specific Observational Campaigns: Over the years, the Government of India has provided support to the Ministry of Earth Science, various national Institutes such as IITs and IISc and universities to improve the observational platforms and modelling capabilities. To enhance the knowledge of air-sea interaction, horizontal and vertical mixing in the upper ocean over different temporal and spatial scales and thereby improving the parameterization schemes in the numerical models, MoES conducted two major observation campaigns in the Bay of Bengal, namely "Ocean Mixing and Monsoon (OMM)" during 2013-2023 and "Bay of Bengal Boundary Layer Experiment (BOBBLE)" during 2016-2021. Both these programmes provided opportunities to survey the upper ocean to understand the ocean mixing, air-sea interactions, and the coupled feedback with the atmospheric boundary layers. In the Arabian Sea regular ship-based observations for process-specific studies funded by MoES provided a much-needed understanding of the upper surface layer processes. To foster research further for enhancing the understanding of the air-sea interactions and their impact on the monsoon, MoES has taken up an India-USA joint study called "Enhancing Knowledge of the Arabian Sea Marine environment through Science and Advanced Training (EKAMSAT)". The main goal of this program is to enhance our understanding of the air-sea interaction over the Arabian Sea to a level that would support the reduction of the systematic errors stemming from the misrepresentation of ocean boundary layer dynamics in models used for the prediction of monsoon rainfall. Sustained observations and process studies to understand the boundary layer processes in the ocean and atmosphere will be the main theme of this collaborative program. Moreover, under the Monsoon

Mission programme, MoES has made coordinated efforts to develop state-of-the-art ocean, weather and climate prediction models, which are now in operational use.

Ocean Modelling and Data Assimilation: MoES is leading the climate and ocean modelling efforts in India. The earth system model developed at the Indian Institute of Tropical Meteorology (IITM), an autonomous body under MoES, participated in the sixth assessment report (AR6) of the Intergovernmental Panel for Climate Change (IPCC). Further, the Indian National Centre for Ocean Information Services (INCOIS), another autonomous institute of MoES is actively involved in numerical ocean modelling activities for operational generation of ocean information and advisory services, and providing ocean analysis, reanalysis and forecasts. Some important operational services include potential fishing zone advisories, harmful algal bloom information, coral bleaching alerts, ocean state forecast, tsunami, cyclone, storm surge early warning services, oil spill trajectory forecasts, marine search and rescue information, etc. Further, the Government has recently approved the Deep Ocean Mission that is being implemented by the MoES. One of the objectives of this Mission, amongst others, is to develop "Ocean Climate Change Advisory Services" that is being implemented by INCOIS to provide future projections of ocean climate change indicators such as sea level rise, cyclones, storm surges, waves, coastal ecology, and assess their impact on the Indian coastal regions through state-of-the-art regional/global dynamical and statistical downscaling and sustained long-term deep ocean observation networks. Under the ambit of Climate Change Division Programme of DST, IIT Madras has established future projection of waves (Bhavithra & Sannasiraj, 2022), storm surges and flooding (Devi et al., 2019) under different RCP scenarios and the resulting impacts on coastal infrastructures (Santosh kumar et al., 2021) has been explored. It is the need of the hour to establish under Shared Socioeconomic Pathways (SSPs) (Saleem Khan et al., 2020).

Knowledge Gaps

India has a very long coastline and therefore is rich in diversity of marine ecosystems. Our coastal waters are also busy with economic activities. Considering that the vulnerability associated with climate change is a combination of physical, biological and socio-economical factors of the region or location, they also depend on the regional geographical features. A relevant challenge is, thus, to develop a suitable approach to assess and project the future changes in the regional physical and ecological properties of the coastal areas along the Indian coastline and the seas around us. Similarly, the mitigation policies and their implementation will also need to be site/region specific.

The primary goal is to provide assessments of coastal erosion and flooding, protection of mangroves, maintain food security, sanitation of drinking water and disease control in the event of extreme sea level rise under the global climate change scenario. One of the major challenges for accurate projections of relative sea level rise is to identify the contribution of various factors amounting to the total regional sea level rise. The inability of coupled climate models to realistically simulate changes in the coastal circulations, uncertainty in the ice loss in the glaciers and ice sheets and isostatic adjustment due to past and ongoing changes in polar ice masses and continental water storage are some of the limitations. The other region-specific changes such as salinity change (also known as halosteric effect), change in interactions between the terrestrial water storage and oceans and sediment transport needs to be studied. The uncertainty associated with the vertical land motion is also a primary limiting information for projecting relative sea level rise. Studies to understand the impact of climate change on extreme events such as storm surges and extreme waves, frequency and intensity of tropical cyclones, extreme rainfall events, etc. as well as to evolve methods to mitigate the socio-economic impacts of such events are also extremely important.

Ecological response to the ongoing and projected climate change, particularly along the coastal waters, is still poorly understood. This lack of monitoring in this part of the world is primarily linked to the unavailability of climate quality observations for ecological and water quality parameters. Though some studies have been undertaken at selected locations along the Indian coasts (e.g., Kochi, Goa, and Vizag), there are limitations on the long-term good quality timeseries data in the Indian Ocean as compared to the Pacific and the Atlantic. Moreover, data collected during various programmes suffer from a lack of standardisation across the data sets and thus, limiting the usability in climate change assessments studies.

Over the last few decades, modelling of the ocean and coupled ocean-atmospheric processes have improved significantly. The availability of higher computing facilities, advancement in model physics, refinement of resolutions and development of efficient data assimilation techniques have led to remarkable improvement in models' prediction skills. As the capacity of high-performing computers increases rapidly, operational centres across the globe are now moving towards high-resolution models of resolution of the order of ~O(1) km scale. Unfortunately, the efficiency of model resolution in the simulation of the north Indian Ocean is still relatively unexplored. While it is evident that eddy-resolving models can produce realistic eddy structures and represent the associated frontal dynamics better than the coarser models, the impact of such improved representation of submesoscale features on the mesoscale simulation is still a subject of debate. It has been observed that significant improvement can be achieved when model resolution increased from coarser $1^o \times 1^o$ to eddy-permitting $0.25^o \times 0.25^o$, but a similar scale of improvement is generally absent when the resolution of the model increased further to eddy-resolving. The very high-resolution models, however, produce better dynamic variables (such as coastal currents, gyres, etc.) (Mathews and Chatterjee, 2022), but do not show similar improvement for the tracers (temperature, salinity, Chlorophyll, etc.). For example, high-resolution models do not show much improvement over the coarser model in simulating mixed-layer depth and evolution of barrier layers in the Bay of Bengal and the Arabian Sea and thus, in upper surface parameters and associated air-sea interaction processes. In fact, Sandery and Sakov (2017) showed that high-resolution sub mesoscale resolving models exhibit lower skill in forecasting mesoscale circulation compared to coarser resolution eddy-resolving models. In a similar line, Sajidh and Chatterjee (2023) showed that while the high-resolution coupled models can better reproduce the Indian Ocean sea level variability, perform poorly when it comes to simulating the mean state. The degradation of model skill in such high-resolution models is likely linked to the misrepresentation of mixing parametrizations which were originally designed for coarser models. Therefore, there is no denying that the high-resolution model of ~O(1 km) scale is needed to meet future requirements, but at the same time, investing in core modelling research to improve the representation of model physics is to be prioritised. It may also be noted that the quality of ocean model simulations heavily depends on the quality of atmospheric forcing fields, particularly in the coastal waters. Hence, improvements in the atmospheric models by which the forcing fields are generated are also important. Regional coupled ocean-atmosphere models are being tested in different ocean prediction centres for improvements in short-term ocean forecasts. Hence, it is desirable to focus on such models as well. Also, development of coastal prediction, particularly the prediction of water quality and ecosystem parameters is closely linked to the dynamics of estuaries as well. Research in this direction also has to be given priority.

Modelling of biogeochemical variables is relatively premature for the Indian Ocean community. However, the recent advancement in regional biogeochemical modelling (Vijith et al., 2016; Chakraborty et al., 2016; Lakshmi et al., 2020) shows promise for future modelling prospects for predicting biogeochemical parameters of the north Indian Ocean. It has been shown that these models do reasonably well in reproducing the seasonal scale of surface biogeochemical parameters, but fail in simulating subsurface and deep ocean features such as subsurface high chlorophyll maxima, spatial extent, magnitude of oxygen minimum zones, etc.

Artificial Intelligence and Machine Learning (AI/ML) techniques and data-driven (deep learning) models are also becoming popular in the area of earth system modelling. However, considering the black-box nature of these models, often the prediction or projections become physically untenable. In order to overcome these lacunae, a hybrid approach by including the inputs from physical processes to the AI-driven models is likely to be way ahead. These approaches have already shown success in other fields, especially in engineering and are now also being tested for climate prediction as well. Considering the ever-evolving nature of this field, dedicated research in this area needs to be entrusted to keep pace with the global community.

All these model development and improvements need to be supported by quality climate observations. While spatial and temporal coverage of the observations are necessary, the continuity of the observation for longer records is key for climate research. Over the last few decades, Indian Ocean observing networks have grown tremendously covering most parts of the north Indian Ocean. However, there are regions of strong air-sea interactions such as the Andaman Sea and the western Arabian Sea where observational networks are still absent. While observational campaigns in the western Arabian Sea are affected by piracy, the logistical difficulty and the presence of other countries' EEZ hinder observations in the Andaman Sea. Further, most of the observation networks focused only to measure the top few hundred of the water column, while the processes due to climate change are most likely evolve in the deeper subsurface layers such as overturning circulations. Therefore, to support the climate research of this basin, sustaining the present observation network is the prerequisite. Further, more autonomous underwater vehicles like deep ocean gliders should be deployed to cover the regions with logistical challenges. These gliders can also be used in monitoring coastal waters more effectively than conventional observation platforms. While INCOIS has started using these glider platforms for continuous observation in the open ocean of the Bay of Bengal and the Arabian Sea, these efforts need to be enhanced to cover a larger area of the north Indian Ocean. In addition, long-term concurrent timeseries measurements of Direct Covariance Fluxes and subsurface parameters, using ship based and INCOIS flux mooring, along with NIOT-OMNI buoy observations at high temporal and vertical resolution will help to identify oceanic processes and improve their representations in the model. Hence, these enhanced monitoring programmes will have to be managed centrally with high-end communication and decision support systems.

Needless to mention, with sufficient knowledgebase been generated, the strategies for adaptation measures to coastal systems must be developed for implementation. The adaptation measures in addition to the present mode of mitigation after the event need detailed study under science and engineering perspectives. Most importantly, all these developments cannot be efficiently done without the involvement of private players. The public-private partnership will be necessary to make these activities competitive and will provide the necessary impetus to emerge as a world leader in this field.

ROADMAP

The great challenge of the climate science community is to **improve the prediction skill of the ocean/climate models for minimising uncertainty and thus, facilitating robust and climate-ready policymaking for adapting and mitigating climate risk.** To achieve this here we proposed a list of some important milestones to be achieved.

- **Sea Level rise**: Sea-level rise is one urgent climate change issue our society is facing, especially for those low-lying regions. The impacts of sea-level rise will be mainly felt through an increased likelihood of extreme sea levels from tides and storm surges, which will increase the frequency and extent of inundation of low-lying coastal areas and infrastructure. Therefore, an integrated approach to study the combined impact of land-surface processes, coastal and open ocean processes and ice-sheets/glaciers is to be adopted.

- **Extreme events:** It is evident from the observations of last few decades that the climate change has substantially influencing the occurrence of extreme events such as the magnitude and frequency of cyclones (Jyotheesh kumar et al., 2020; 2021; Kiran and Balaji, 2022) and rainfall pattern variation. These changes have been influencing coastal erosion/ accretion, fishing zones and seawater intrusion. The detailed analysis of such events with the increased on the present state-of-the art knowledge on the modelling and monitoring framework is essential with various data mining tools along with modelling.

- **High-resolution model development and data assimilation techniques**: Development of ocean circulation and regional coupled models for climate research and operational predictions will have to be prioritized. There is an immediate need to build an ocean general circulation model to resolve sub-kilometre scale processes to help in downscaling the impacts of climate change for the regional seas. A holistic approach to enhance our understanding using a hierarchy of models starting from process-specific models to complex ocean general circulation models for enabling improved model physics is to be adopted. Data assimilation methods have to be improved for preparing ocean analysis/reanalysis products. These techniques have to be fine-tuned keeping in view of the requirements in high-resolution models as well as availability of data with varying spatial and temporal frequency. A parallel approach to infuse physics-aware AI/ML techniques for improving predictability needs to be prioritized. Most importantly, building partnerships with private players will enhance the efficiency and fast-track the developments.

- **Modelling ecosystems and higher trophic levels**: Existing ecosystem modelling efforts are at a novice stage and rely heavily on unresolved/unknown processes through broad parametrization. Thus, the accuracy of these models suffers from large bias even for the lower trophic levels. The modelling of higher trophic levels is further premature. Greater participation of researchers, including stronger collaboration between observationalists and modellers, is needed to improve the biogeochemical parametrizations backed by high-resolution observations.

- **Observations**: The existing observation networks are primarily focused on observing the upper ocean processes and very limited observations are available for the deep ocean. However, the signature of climate change is more prominent in the subsurface and deeper layers. In order to understand and assess the future impact of climate change observation from the deeper layer of the ocean is necessary. The enhancement of measuring platforms such as Autonomous Ocean Observation Systems (AOOS) are future needs to meet the increasing demand for advanced monitoring techniques and the systematic maintenance of ocean data collection requirements. Indigenous development of oceanographic instruments/sensors for cost-effective ocean observations will be the key for success in sustained long-term, continuous, ocean observation networks. Efforts should be strengthened to develop new generation satellite remote sensing sensors to measure all ocean variables at high temporal, spatial and spectral resolutions. Satellite communication techniques should be developed to enable effective and efficient communication of data from in-situ ocean observing platforms.

- **Capacity building**: The heart of building and sustaining resilience against climate change-induced risk is to continuously infuse a pool of experts through training and PhD and Post−Doctoral Research programmes. Regular training sessions, workshops and symposiums have to be organised to improve the opportunities for researchers to interact and exchange their research findings and ideas. Establishing visiting faculty positions in the leading Indian organisations to accommodate experts working in ocean sciences will provide excellent opportunities to our researchers to improve their skills and infuse fresh research ideas.

Further, while climate change mostly makes adverse impact, it also can provide opportunities. For example, increased warming of the upper ocean can lead to increased stratification which may allow efficient electricity generation through the ocean thermal energy conversion (OTEC). Similarly, increased wave activities in the climate change scenarios can also provide a better opportunity to generate electricity. These can become a potential source for the future power requirement of our country. India should tap on such future opportunities its favour to become a leader in this, and other relevant sectors.

REFERENCES

Abram, N. J., Wright, N. M., Ellis, B., Dixon, B. C., Wurtzel, J. B., England, M. H., et al. (2020). Coupling of Indo-Pacific climate variability over the last millennium. Nature, 579(7799). https://doi.org/10.1038/s41586-020-2084-4

Bierkandt, R., Auffhammer, M., & Levermann, A. (2015). US power plant sites at risk of future sea-level rise. Environmental Research Letters, 10(12). https://doi.org/10.1088/1748-9326/10/12/124022

Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., et al. (2019). Changing ocean, marine ecosystems, and dependent communities.

Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Aristegui, J., Guinder, V. A., Hallberg, R., et al. (2019). Changing Ocean, Marine Ecosystems, and Dependent Communities (09 SROCC Ch05 FINAL-1). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, (January).

Bhavithra, R. S., & Sannasiraj, S. A. (2022). Climate change projection of wave climate due to Vardah cyclone in the Bay of Bengal. Dynamics of Atmospheres and Oceans, 97, 101279.

Cáceres, D., Marzeion, B., Malles, J. H., Gutknecht, B. D., Schmied, H. M., & Döll, P. (2020). Assessing global water mass transfers from continents to oceans over the period 1948–2016. Hydrology and Earth System Sciences. https://doi.org/10.5194/hess-24-4831-2020

Chakraborty, K., Gupta, A., Lotliker, A. A., & Tilstone, G. (2016). Evaluation of model simulated and MODIS-Aqua retrieved sea surface chlorophyll in the eastern Arabian Sea. Estuarine, Coastal and Shelf Science, 181. https://doi.org/10.1016/j.ecss.2016.08.002

Chandra Mohanty, P. (2017). Coral Bleaching Along Andaman Coast Due to Thermal Stress During Summer Months of 2016: A Geospatial Assessment. American Journal of Environmental Protection, 6(1). https://doi.org/10.11648/j.ajep.20170601.11

Chatterjee, A., Anil, G., & Shenoy, L. R. (2022). Marine heatwaves in the Arabian Sea. Ocean Science, 18(3). https://doi.org/10.5194/os-18-639-2022

Clarke, T. M., Wabnitz, C. C. C., Striegel, S., Frölicher, T. L., Reygondeau, G., & Cheung, W. W. L. (2021). Aerobic growth index (AGI): An index to understand the impacts of ocean warming and deoxygenation on global marine fisheries resources. Progress in Oceanography. https://doi.org/10.1016/j.pocean.2021.102588

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other CO2 problem. Annual Review of Marine Science. https://doi.org/10.1146/annurev.marine.010908.163834

Devi, N. N., Sridharan, B., & Kuiry, S. N. (2019). Impact of urban sprawl on future flooding in Chennai city, India. Journal of Hydrology, 574, 486-496.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436(7051). https://doi.org/10.1038/nature03906

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., et al. (2020). The causes of sea-level rise since 1900. Nature, 584(7821). https://doi.org/10.1038/s41586-020-2591-3

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. Nature, 560(7718). https://doi.org/10.1038/s41586-018-0383-9

Gadgil Sulochana, Mark A Cane and Francis P. A. (2023), On rogue La Niñas, with below average monsoon rainfall, J. Earth Sys. Sci. (in press).

Geetha, B., & Balachandran, S. (2014). Decadal variations in translational speed of cyclonic disturbances over North Indian Ocean. Mausam. https://doi.org/10.54302/mausam.v65i1.934

Gupta, G. V. M., Thottathil, S. D., Balachandran, K. K., Madhu, N. V., Madeswaran, P., & Nair, S. (2009). CO2 supersaturation and net heterotrophy in a tropical estuary (Cochin, India): Influence of anthropogenic effect: Carbon dynamics in tropical Estuary. Ecosystems, 12(7). https://doi.org/10.1007/s10021-009-9280-2

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. Science, 319(5865). https://doi.org/10.1126/science.1149345

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., et al. (2017). Global warming and recurrent mass bleaching of corals. Nature, 543(7645). https://doi.org/10.1038/nature21707

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Cambridge University Press. In Press.

Jackson, J. B. C. (2010). The future of the oceans past. Philosophical Transactions of the Royal Society B: Biological Sciences. https://doi.org/10.1098/rstb.2010.0278

Jyoteeshkumar Reddy, P., Sriram, D., Gunthe, S. S., & Balaji, C. (2021). Impact of climate change on intense Bay of Bengal tropical cyclones of the post-monsoon season: a pseudo global warming approach. Climate Dynamics, 56(9), 2855-2879.

Jyoteeshkumar, P., Kiran, P. V., & Balaji, C. (2020). Chennai extreme rainfall event of 2015 under future climate projections using the pseudo global warming dynamic downscaling method. Current Science (00113891), 118(12).

Kiran, P. V. and Balaji, C. (2022). The future projection of Cyclones in Bay of Bengal: a study using coupled ocean atmospheric model, Ocean Dynamics, Springer.

Kumar, K. K., Rajagopalan, B., & Cane, M. A. (1999). On the weakening relationship between the indian monsoon and ENSO. Science, 284(5423). https://doi.org/10.1126/science.284.5423.2156

Kumar, S. P., Roshin, R. P., Narvekar, J., Kumar, P. K. D., & Vivekanandan, E. (2009). Response of the Arabian Sea to global warming and associated regional climate shift. Marine Environmental Research, 68(5). https://doi.org/10.1016/j.marenvres.2009.06.010

Lakshmi, R. S., Chatterjee, A., Prakash, S., & Mathew, T. (2020). Biophysical Interactions in Driving the Summer Monsoon Chlorophyll Bloom Off the Somalia Coast. Journal of Geophysical Research: Oceans, 125(3). https://doi.org/10.1029/2019JC015549

Li, B., Zhou, L., Qin, J., & Murtugudde, R. (2022). Increase in intraseasonal rainfall driven by the Arabian Sea warming in recent decades. Geophysical Research Letters, 49(20), e2022GL100536.

Lotliker, A. A., Baliarsingh, S. K., Samanta, A., & Varaprasad, V. (2020). Growth and Decay of High-Biomass Algal Bloom in the Northern Arabian Sea. Journal of the Indian Society of Remote Sensing, 48(3). https://doi.org/10.1007/s12524-019-01094-3

Mathew, T., Chatterjee, A., Shenoy, L. R., & Prakash, S. (2022). Impact of model resolution on the sea level simulation of the north Indian Ocean. Authorea Preprints.

Mohanty, P. C., Mahendra, R. S., Bisoyi, H., Kumar Tummula, S., Grinson, G., Nayak, S., & Kumar Sahu, B. (2013a). Assessment of the coral bleaching during 2005 to decipher the thermal stress in the coral environs of the Andaman Islands using remote sensing. European Journal of Remote Sensing. https://doi.org/10.5721/EuJRS20134624

Mohanty, P. C., Mahendra, R. S., Bisoyi, H., Kumar Tummula, S., Grinson, G., Nayak, S., & Kumar Sahu, B. (2013b). Assessment of the coral bleaching during 2005 to decipher the thermal stress in the coral environs of the Andaman Islands using remote sensing. European Journal of Remote Sensing, 46(1). https://doi.org/10.5721/EuJRS20134624

Mohapatra, M., Geetha, B., Balachandran, S., & Rathore, L. S. (2015). On the Tropical Cyclone Activity and Associated Environmental Features over North Indian Ocean in the Context of Climate Change. Journal of Climate Change, 1(1,2). https://doi.org/10.3233/jcc-150001

Nieves, V., Willis, J. K., & Patzert, W. C. (2015). Recent hiatus caused by decadal shift in Indo-Pacific heating. Science, 349(6247). https://doi.org/10.1126/science.aaa4521

Rathore, S., Goyal, R., Jangir, B., Ummenhofer, C. C., Feng, M., & Mishra, M. (2022). Interactions Between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. Front. Clim. 4: 861477. Doi: 10.3389/Fclim.

Do Rosário Gomes, H., Goes, J. I., Matondkar, S. G. P., Buskey, E. J., Basu, S., Parab, S., & Thoppil, P. (2014). Massive outbreaks of Noctiluca scintillans blooms in the Arabian Sea due to spread of hypoxia. Nature Communications, 5. https://doi.org/10.1038/ncomms5862

Roxy, M. K., Ritika, K., Terray, P., & Masson, S. (2014). The curious case of Indian Ocean warming. Journal of Climate. https://doi.org/10.1175/JCLI-D-14-00471.1

Sajidh, C. K., & Chatterjee, A. (2023). Indian Ocean dynamic sea level, its variability and projections in CMIP6 models. Climate Dynamics, 1–24.

Saleem Khan, A., Sabuj Kumar, M., Sudhir Chella, R., & Devdyuti, B. (2020). BASIEC: a coastal climate service framework for community-based adaptation to rising sea-levels. In Handbook of Climate Services (pp. 11-31). Springer, Cham.

Sandeep, S., & Ajayamohan, R. S. (2015). Poleward shift in Indian summer monsoon low level jetstream under global warming. Climate Dynamics, 45(1–2). https://doi.org/10.1007/s00382-014-2261-y

Santosh Kumar, B., Sannasiraj, S. A., & Murali, K. (2021). Effect of Climate Change in the Deterioration of a Berthing Structure in a Tropical Environment. Journal of The Institution of Engineers (India): Series A, 102(3), 697-703.

Saranya, J. S., Roxy, M. K., Dasgupta, P., & Anand, A. (2022). Genesis and Trends in Marine Heatwaves Over the Tropical Indian Ocean and Their Interaction With the Indian Summer Monsoon. Journal of Geophysical Research: Oceans, 127(2). https://doi.org/10.1029/2021JC017427

Srinivasu, U., Ravichandran, M., Han, W., Sivareddy, S., Rahman, H., Li, Y., & Nayak, S. (2017). Causes for the reversal of North Indian Ocean decadal sea level trend in recent two decades. Climate Dynamics, 49(11–12). https://doi.org/10.1007/s00382-017-3551-y

Storlazzi, C. D., Gingerich, S. B., Van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., et al. (2018). Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. Science Advances, 4(4). https://doi.org/10.1126/sciadv.aap9741

Swapna, P., Jyoti, J., Krishnan, R., Sandeep, N., & Griffies, S. M. (2017). Multidecadal Weakening of Indian Summer Monsoon Circulation Induces an Increasing Northern Indian Ocean Sea Level. Geophysical Research Letters, 44(20). https://doi.org/10.1002/2017GL074706

The Indian Express, O. (2015). India to surpass China by 2022 to become world ’ s most populous nation. The Indian Express.

Unnikrishnan, A. S., & Shankar, D. (2007a). Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? Global and Planetary Change. https://doi.org/10.1016/j.gloplacha.2006.11.029

Unnikrishnan, A. S., & Shankar, D. (2007b). Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? Global and Planetary Change, 57(3–4). https://doi.org/10.1016/j.gloplacha.2006.11.029

United Nations Department of Economic and Social Affairs, Population Division (2022). World Population Prospects 2022: Summary of Results. UNDESA/POP/2022/TR/NO. 3.

Vijith, V., Vinayachandran, P. N., Thushara, V., Amol, P., Shankar, D., & Anil, A. C. (2016). Consequences of inhibition of mixed-layer deepening by the West India Coastal Current for winter phytoplankton bloom in the northeastern Arabian Sea. Journal of Geophysical Research: Oceans, 121(9). https://doi.org/10.1002/2016JC012004

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Atmospheric science: Changes in tropical cyclone number, duration, and intensity in a warming environment. Science, 309(5742). https://doi.org/10.1126/science.1116448

Yang, L., Murtugudde, R., Zhou, L., & Liang, P. (2020). A Potential Link Between the Southern Ocean Warming and the South Indian Ocean Heat Balance. Journal of Geophysical Research: Oceans, 125(12). https://doi.org/10.1029/2020JC016132

Zhang, Y., Zhou, W., Wang, X., Chen, S., Chen, J., & Li, S. (2022). Indian Ocean Dipole and ENSO’s mechanistic importance in modulating the ensuing-summer precipitation over Eastern China. Npj Climate and Atmospheric Science, 5(1), 48.

CHAPTER 4: AEROSOL-CLIMATE INTERACTIONS

V Vinoj and Sagnik Dey

Coordinating Lead Author
Prof. V Vinoj, IIT Bhubaneshwar

Lead Authors
Prof. Sagnik Dey, IIT Delhi

BACKGROUND

Atmospheric aerosols are tiny particles suspended in the atmosphere with a typical size range of 10^{-2} to 10^{2} µm. They are emitted into the atmosphere due to both natural and anthropogenic causes. The wind-blown sea spray, soil and mineral dust from semi-arid and deserts, volcanic eruption and biogenic emissions are natural aerosols. In contrast, sulphate and carbonaceous aerosols come from power plants, industrial emissions, and fossil fuel combustion are anthropogenic aerosols (Carslaw et al. 2010). The biomass burning from natural forest or deliberate fires could be classified as natural or anthropogenic. Some aerosols are emitted directly into the atmosphere as primary particles, while others form through the gas-to-particle conversion process called secondary aerosols (Leaitch et al., 1999; Kulmala et al., 2017).

The aerosols scatter and absorb solar and terrestrial radiation and modulate the Earth's radiation budget, known as the direct radiative effect (Haywood et al., 1997, 1999). The direct effects of aerosols are related to how they absorb and scatter shortwave and longwave radiation. Their physicochemical properties determine whether the aerosols are absorbing or scattering. For example, sea-salt, nitrate and sulphate aerosols scatter a significant fraction of the incoming solar radiation back into space, leading to cooling (Coakley, 2005). Mineral dust and Black carbon (BC) due to its absorption of solar radiation, tends to warm the atmosphere (Ginoux, 2017; Gustafson and Ramanathan, 2016). The scattering aerosols increase the fraction of solar radiation reflected back to space leading to regional and global scale cooling. On the other hand, absorbing aerosols depending on their vertical distribution and their relative presence above a cloud layer or above bright surface tends to have enhanced warming (Satheesh, 2002; Chand et al., 2012). Such atmospheric warming at different altitudes can have differing climate effects either through their effect on the overall energy balance or through changes in atmospheric stability and related weather parameters (Xu et al., 2017). Thus overall warming or cooling of the column depends on the relative strength of scattering and absorbing aerosols which in turn is a function of aerosol type, size, and chemical composition. Single scattering albedo (SSA) is an important parameter which is the ratio of scattering to extinction of aerosols and provides the much important scattering-absorption partitioning information of aerosols. Despite its importance, quality controlled global scale measurements of SSA are still lacking (Devi et al., 2022; Satheesh et al., 2009).

The aerosols also alter cloud formation and growth thereby modifying the shortwave and/or longwave radiation known as the indirect effects (Chan et al., 2013). High aerosol loading in the atmosphere can lead to clouds with more, but smaller, water droplets than clouds with the same water content formed in relatively cleaner areas. The clouds thus formed are more reflecting (i.e., have a higher albedo), inducing a negative radiative forcing referred to as the first indirect, the cloud-albedo, or the Twomey effect (Twomey et al., 1977). These clouds whose life is enhanced due to aerosol effects tend to stay in the atmosphere longer. This effect is called the aerosol second indirect effect or the aerosol lifetime effect (Lohmann et al., 2005). Also, when mixed with clouds, absorbing aerosols and its associated warming can enhance the evaporation of cloud droplets (called the aerosol semi-direct effect) (Ackerman et al., 2000). Thus, these effects can change clouds' microphysical, radiative properties, frequency, and lifetimes. This in slightly longer time scales can alter precipitation characteristics thereby affecting precipitation susceptibility (Sorooshian et al., 2009) and hence efficiency thereby altering the radiation balance and its spatial and temporal characteristics. In addition, absorbing aerosols such as BC and dust deposition on glaciers and ice-sheets can alter the planetary albedo and also lead to their melting thereby impacting the water cycle and thus regional water security (Barnett et al., 2005; Hock et al., 2019; Raveillet et al., 2022).

As per Intergovernmental Panel on Climate Change (IPCC), in our knowledge of anthropogenic climate change, aerosols are estimated to have the second most significant radiative forcing behind greenhouse gases (GHG's) (Boucher et al., 2013; IPCC, 2013). However, in terms of uncertainties aerosols ranks first. It is estimated that the aerosol radiative effect is ~ -1.3+/-0.7 W/m2. Of this, -0.3+/-0.3 W/m2, is attributed to the direct effect, and -1.0 +/-0.7 W/m2 to the indirect effect. Thus, both direct effect and indirect effect of aerosols exhibit large uncertainty in our understanding of anthropogenic climate change (Boucher et al., 2013; IPCC, 2013).

The uncertainties in aerosol-climate effects both globally and regionally are due to inaccurate constraints on aerosol optical, microphysical (size distribution, optical depth, hygroscopicity and mixing state), chemical composition, vertical distribution, long range transport and inadequate process level understanding and their representation in climate models. It may be mentioned that the IPCC defined uncertainties are mostly due to inter-model differences and represents the variability between different models with varied sophistication and process level representation of aerosol effects (Lee et al., 2016). Unlike GHG's, aerosols due to their short residence times and different emission sources, aerosols are more concentrated closer to their origins and exhibit significant spatiotemporal variability. Even if all parameters were well represented, uncertainties related to simple processes such as dry and wet removal can lead to erroneous long range transport spatially leading to overall uncertainties in global and regional radiative effects with implication to the overall climate sensitivity. Thus understanding of aerosols, their sources, sizes, chemical composition, vertical distribution, long range transport, scattering- absorption partitioning, hygroscopicity, mixing, representation of processes etc, all leads to significant uncertainties in our understanding of their climate effects. Thus systematic and focused studies addressing various aspects related to aerosols are important if one needs to understand anthropogenic climate change. Studies addressing a sub-set of aerosols such as those related to air quality especially related to particulate matter could significantly supplement the aerosol studies and contribute to our understanding.

Indian Scenario

India represents a unique case for aerosol loading, properties and their effects. Varying aerosol sources get activated at different spatial and temporal scales. For example, natural dust gets activated during pre-monsoon and monsoon periods over the North-west of the Indian sub-continent (Dey et al., 2004, Jethva et al., 2005, Deepshikha et al., 2006). On the other hand, this source weakens as a consequence of both changing air mass and other atmospheric processes during winter and post-monsoon season when anthropogenic aerosols dominate the aerosol loading over the Indian subcontinent (Reddy and Venkatraman, 2000, Vinoj and Pandey, 2022). This is also the period when biomass burning due to both natural and anthropogenic causes leads to additional loading (Mukherjee et al., 2018). Monsoon period suppresses aerosol loading through the wet removal process in the lower part of the atmosphere (Liu et al., 2011). These changing nature of aerosols temporally and spatially (Moorthy et al., 2013) when coupled with different land use nature across India, produces a very complex aerosol radiation-cloud-precipitation-climate interaction. Making this region a globally important region where aerosol climate coupling is quite strong. In addition, the rapidly changing nature of anthropogenic and natural aerosol loading, which includes the increasing biomass burning (Innes, 2000) both as a consequence of climate change and anthropogenic activities, increasing scattering aerosols such as sulphate (Lu et al., 2013) and nitrate due to rapid economic growth, changing mineral dust (Pandey et al., 2017) due to regional climate change and observed decline in black carbon (Manoj et al., 2019) due to better emission controls and efficient burning of fuels etc are all making the overall aerosol-climate coupling over India very complex. In addition, the large spatio-temporal variability makes aerosols one of the most important components in the studies related to both global and regional climate change.

Over India, traditionally, organized network aerosol observational studies started around 1985 (under the Indian Space Research Organization's (ISRO), Aerosol Radiative Forcing over India Network (ARFINET) under ISRO's Geosphere Biosphere Program) (Moorthy et al., 2013). This network has now expanded to over 40 stations focusing primarily on characterising the optical properties especially using the indigenously developed Multi Wavelength solar Radiometer (MWR) in different environments. They followed similar protocols as followed by global networks such as National Atmospheric and Space Administration (NASA), Aerosol Robotic Network (AERONET) (Holben et al., 1998) and provided significant long term measurements and insights into estimation of aerosol direct effect over different environments over the Indian region (Moorthy et al., 2013). In addition, this initiative has immensely contributed to scientific capacity building, inter-institutional collaborations sustained over several decades. In addition, several campaign mode studies such as ship based Arabian Sea Monsoon Experiment (ARMEX - I and II) (Moorthy et al., 2005; Rao, 2005), ship, aircraft and land based Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) (Moorthy et al., 2008), Winter Integrated Campaign for Aerosols, gases and Radiation Budget (W-ICARB), Regional Aerosol Warming EXperiment (RAWEX) (Moorthy et al., 2016), Land Campaign- I & II (Moorthy et al., 2005) etc all initiated under the ARFINet investigators. The experiments over the oceans were initiated to understand aerosol properties, radiative effect and long-range transport over the oceanic regions around India (Arabian Sea and Bay of Bengal). These studies on a smaller scale were further extended to Antarctica (Chaubey et al., 2010) and the Arctic (Gogoi et al., 2016) by different institutions in India including ISRO and NCPOR in recent times. In addition, there were other international campaigns such as the Indian Ocean Experiment (INDOEX) (Mitra et al., 2003), The South West Asian Aerosol-Monsoon Interactions (SWAAMI) (Pathak et al., 2019), NASA's TIGREZ campaign involving scientists from both India and abroad to understand various aspects related to aerosols. Most of these campaigns, especially those by ISRO, addressed problems of interest and relevance to the ARFI program bridging knowledge gaps on aerosols and their climate effects over the Indian region. It may be mentioned that except MWR developed by ISRO, most aerosol instruments used in these campaigns have a foreign origin. These network observations must be further strengthened and expanded to include additional sites and state of the art instrumentation to also elucidate information on other new aerosol species that are evolving (e.g. biological aerosols) and those including aerosol absorption and chemical composition.

The vertical profiling of aerosol properties using network observations must also be initiated similar to MPLNET (Welton et al., 2018). Existing satellite based active aerosol measurements and the future multi-spectral, multi-angle polarimeter imagers such as for example, the NASA's HARP-2 on Plankton, Aerosol, Clouds, Ocean Ecosystem (PACE) mission could be systematically studied in conjunction with surface measurements for its widespread use to understand regional aerosol effects (add).

During the period 2009 to 2015, campaign mode measurements were made to understand the aerosol indirect effects under the campaign named the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAAIPEX) (Prabha et al., 2011). This experimental campaign included dedicated aircraft and other specialised measurements to elucidate the physics and dynamics of aerosol- cloud-precipitation interactions. In addition, this campaign also focused on understanding the scientific basis for cloud droplet and raindrop formation in pre-monsoon and monsoon clouds and how aerosol pollution influences these processes (Prabha et al., 2011, 2019). Much insights were obtained on both indirect and semi-direct aerosol effects.

Thus excellent efforts were made nationally in characterising aerosol properties and their effects over the Indian region. Studies using satellite datasets over India, primarily depend on quality assured datasets from external agencies such as NASA, ESA or JAXA. Aerosol datasets from Indian satellites (Mishra et al., 2014) must be improved and made available for future studies. Active and passive sensors specifically for aerosols and clouds must be initiated.

However, relatively few studies existed originating from Indian labs in understanding aerosol impacts or hypotheses (Chandra et al., 1999) on locally relevant issues such as monsoon rainfall (Vinoj et al., 2014, Das et al., 2015, Singh et al., 2019), tropical cyclones, extreme precipitation (ref) etc. Most of such initiatives until recently were initiated by research groups abroad (Bollasina et al., 2011; Lau et al., 2006, Ganguly et al., 2011) or by a handful of isolated Indian researchers (Das et al., 2015, Singh et al., 2019, Ayantika et al., 2021, Nandini et al., 2022, Debnath et al., 2023). This has been changing, but at a slow pace. These are the result of lack of availability of expertise in including interactive aerosol and atmospheric chemistry in regional and global climate models. One of the roadblocks even for using models developed elsewhere has been the lack of availability of high resolution emission inventories relevant for India. Another challenge is the lack of critical infrastructure and manpower trained with aerosol modeling experience. Both these limitations have held back aerosol-monsoon or other impact studies over India.

These efforts must progress along with development of modeling expertise and models for India. Such a synergistic approach to improve observations and modeling will help with our understanding of aerosols and climate interactions over the Indian subcontinent.

KEY OBJECTIVES

1. Strengthen the observational capability of aerosol physical, optical, chemical and other properties using ground, ship, satellite and aerial and space based platforms along with concomitant cloud and other supplementary measurements relevant for radiation and cloud interaction studies in different environmental setting including mountains, plains, ocean and islands.
2. Develop indigenous instrument capability for ground, airborne and satellite instruments (aerosols and atmospheric chemistry).
3. Develop expertise in both satellite and modeling capability related to both use and development.
4. Encourage impact assessment studies to understand aerosol local impacts.
5. Aerosol modelling for air quality applications
6. Develop capability for climate modeling and projection using preferably an Indian modeling infrastructure.

ROADMAP

Short term Goals (2030)

1. Expansion of the ground based observational network for aerosols and other allied essential climate variables (include state of the art measurements that helps in understanding scattering-absorption partitioning of aerosols, aerosol species measurements etc). This has to be enabled both at the surface and in the vertical column using appropriate measurement techniques (e.g. development of a LIDAR including polarization capability).
2. Expansion of campaign mode targeted research activities over land and ocean including those related to understanding marine aerosols, dust deposition, long range transport and related bio-geochemical processes over oceanic regions around India.
3. Understanding the effect of aerosols on mixed phase clouds with emphasis on ice nucleation particles (INP) to obtain insight into both aerosol-cloud interactions and extreme precipitation.
4. Design, develop capability in better retrieval of aerosol properties over land (with thrust on using Indian satellites with possibly enhanced follow up missions for continuity in the long term). This could be carried out in collaboration with Indian Space Research Organization, research and academic institutes. This must include widespread usage, validation and improvement of foreign and Indian satellite aerosol retrievals. Specific focus must be provided to retrievals using polarization measurements that are capable of providing additional insights into aerosol properties such as aerosol shape, type and absorption.
5. Understand the aerosol-induced snow darkening, their long term changes using in situ, satellite and model studies to understand river runoff and hydrological cycle over the Himalayas.
6. Develop expertise in implementing interactive aerosol modules in both regional and global climate models within the country (with sophistication ranging from process scale models to large eddy simulations, regional to global climate models).

7. Develop updatable high-resolution emission inventories for modelling aerosol related impacts for the Indian region. This initiative could be carried out in collaboration with the National Clean Air Program (MoEFCC's NCAP) Network and other related programs. Such initiatives will provide precious datasets for current future research activities including climate projections.
8. Specific modules could be included to encourage aerosol-monsoon, aerosol-air quality and aerosol-tropical cyclone related studies to understand aerosol regional climate impacts.
9. Establish a technological ecosystem and associated technologies to design and develop ground-based, air-borne, and space-borne instrumentation for aerosol research within the country.

Long term Goals (beyond 2030)

1. The long-term observations must be maintained in conjunction with development of Indian climate models with interactive aerosols and chemistry for deducing the long-term aerosol-related effects upon climate and associated feedback. Such efforts should be developed by standardized measurements technologies and methods to precisely quantify anthropogenic forcing due to aerosols. Such capability will help India's plan for mitigation and adaptation policies.

2. Quantitative and qualitative understanding on effects of aerosols on monsoon, tropical cyclones and global warming for appropriate future policy support.

REFERENCES

Ackerman, S., O. B. Toon, D. E. Stevens, A. J. Heymsfield, V. Ramanathan, and E. J. Welton, 2000: Reduction of tropical cloudiness. Science, 288 , 1042–1047.

Ayantika, D. C., R. Krishnan, M. Singh, P. Swapna, N. Sandeep, A. G. Prajeesh, and R. Vellore, 2021: Understanding the combined effects of global warming and anthropogenic aerosol forcing on the South Asian monsoon. Climate Dyn., 56, 1643–1662, https://doi.org/10.1007/s00382-020-05551-5.

Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309 (2005)

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Carslaw, K.S., Boucher, O., Spracklen, D. V., Mann, G.W., L. Rae, J.G., Woodward, S., Kulmala, M., 2010. A review of natural aerosol interactions and feedback within the Earth system. Atmos. Chem. Phys. 10, 1701–1737. https://doi.org/10.5194/ACP-10-1701-2010

Coakley, J., 2005, Reflections on aerosol cooling: Nature, v. 438, p. 1091–1092, doi: 10.1038/4381091a.

Chandra Venkataraman, et al. “Anthropogenic sulphate aerosol from India: estimates of burden and direct radiative forcing.” Atmospheric Environment 33 (1999): 3225-3235.

Chaubey, J. P., K. K. Moorthy, S. S. Babu, V. S. Nair, and A. Tiwari (2010), Black carbon aerosols over coastal Antarctica and its scavenging by snow during the Southern Hemispheric summer, J. Geophys. Res., 115, D10210, doi:10.1029/2009JD013381

Deepshikha. S, S.K. Satheesh, J. Srinivasan (2006), Dust aerosols over India and adjacent continents retrieved using METEOSAT infrared radiance part I: sources and regional distribution, Ann. Geophys., 24, pp. 37-61, 10.5194/angeo-24-37-2006

Devi, A.; Satheesh, S.K. (2022), Global maps of aerosol single scattering albedo using combined CERES-MODIS retrieval. Atmos. Chem. Phys. Discuss. 2022, 22, 5365–5376.

Ginoux, P (2017).: Warming or cooling dust?, Nat. Geosci., 10, 246–248, https://doi.org/10.1038/ngeo2923.

Gustafsson and Ramanathan, 2016, Convergence on climate warming by black carbon aerosols Proc. Natl. Acad. Sci., 113, pp. 4243-4245

Ghan, S. J. et al. A simple model of global aerosol indirect effects. J. Geophys. Res. Atmos. 118, 6688–6707 (2013).

Haywood, J.M., Ramaswamy, V., Soden, B.J., 1999. Tropospheric aerosol climate forcing in clear-sky satellite observations over the oceans. Science 283, 1299–1303

Haywood, J.M., et al., 1997. General circulation model calculations of the direct radiative forcing by anthropogenic sulfate and fossil-fuel soot aerosol. Journal of Climate 10 (7), 1562–1577

Hock, R. et al. High mountain areas: IPCC special report on the ocean and cryosphere in a changing climate (2019)

IPCC, Summary for Policymakers. Climate Change 2013: The Physical Science Basis, eds T Stocker, et al. (Cambridge Univ Press, New York), pp. 1–29 (2013).

Innes, J.L. (2000). Biomass Burning and Climate: An Introduction. In: Innes, J.L., Beniston, M., Verstraete, M.M. (eds) Biomass Burning and Its Inter-Relationships with the Climate System. Advances in Global Change Research, vol 3. Springer, Dordrecht. https://doi.org/10.1007/0-306-47959-1_1

Jethva, H., S. K. Satheesh, and J. Srinivasan (2005), Seasonal variability of aerosols over the Indo-Gangetic basin, *J. Geophys. Res.*, 110, D21204, doi:10.1029/2005JD005938.

Kulmala, M., Kerminen, V. M., Petaja, T., Ding, A. J. & Wang, L. Atmospheric gasto-particle conversion: why NPF events are observed in megacities? Faraday Discuss. 200, 271–288 (2017).

Liu X D, Yan L B, Yang P, Yin Z Y, North G R. 2011. Influence of Indian summer monsoon on aerosol loading in East Asia. J Appl Meteor Clim, 50: 523–533

Lu Z, Streets DG, de Foy B, Krotkov NA. 2013. Ozone Monitoring Instrument observations of interannual increases in SO2 emissions from Indian coal-fired power plants during 2005–2012. Environ Sci Technol. 47(24):13993–14000.

Leaitch, W. R., Bottenheim, J. W., Biesenthal, T. A., Li, S.-M., Liu, P. S. K., Asalian, K.,

Dryfhout-Clark, H., Hopper, F., and Brechtel, F. (1999), A case study of gas-to-particle conversion in an eastern Canadian forest, J. Geophys. Res., 104(D7), 8095– 8111, doi:10.1029/1998JD100012.

Lee, Lindsay & Reddington, Carly & Carslaw, Kenneth. (2016). On the relationship between aerosol model uncertainty and radiative forcing uncertainty. Proceedings of the National Academy of Sciences of the United States of America. 113. 10.1073/pnas.1507050113

Lohmann, U., and J. Feichter (2005), Global indirect aerosol effects: A review, Atmos. Chem. Phys., 5, 715– 737, doi:10.5194/acp-5-715-2005.

M. Manoj, S. Satheesh, K.K. Moorthy, M.M. Gogoi, S.S. Babu (2019), Decreasing trend in black carbon aerosols over the indian region, Geophys. Res. Lett., 46 , pp. 2903-2910

Moorthy, K. Krishna, et al. "Evolution of Aerosol Research in India and the RAWEX–GVAX: An Overview." *Current Science*, vol. 111, no. 1, 2016, pp. 53–75.

Moorthy, K. K., Satheesh, S. K., Babu, S. S., & Dutt, C. B. S. (2008). Integrated campaign for aerosols, gases and radiation budget (ICARB): an overview. *Journal of Earth System Science*, *117*, 243-262.

Moorthy, K. K., et al. (2005b), Wintertime spatial characteristics of boundary layer aerosols over Peninsular India, J. Geophys. Res., 110, D08207, doi:10.1029/2004JD005520

Mukunda M. Gogoi, S. Suresh Babu, K. Krishna Moorthy, Roseline C. Thakur, Jai Prakash Chaubey, Vijayakumar S. Nair, Aerosol black carbon over Svalbard regions of Arctic, Polar Science, Volume 10, Issue 1, 2016, Pages 60-70, ISSN 1873-9652, https://doi.org/10.1016/j.polar.2015.11.001.

Mukherjee. T, A. Asutosh, S. K. Pandey, L. Yang, A. Panwar, P. P. Gogoi and V. Vinoj (2018), Increasing Potential for Air Pollution over Megacity New Delhi: A Study Based on 2016 Diwali Episode, Aerosol and Air Quality Research, DOI: 10.4209/aaqr.2017.11.0440

Mishra M K, Rastogi G and Chauhan P 2014 Operational retrieval of aerosol optical depth over Indian subcontinent and Indian Ocean using INSAT3D/IMAGER and product validation; Hyderabad, India*: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-8, 2014, ISPRS Technical Commission VIII Symposium, 09–12 Dec 2014.*

Pathak, H. S., Satheesh, S. K., Nanjundiah, R. S., Moorthy, K. K., Lakshmivarahan, S., and Babu, S. N. S.: Assessment of regional aerosol radiative effects under the SWAAMI campaign – Part 1: Quality-enhanced estimation of columnar aerosol extinction and absorption over the Indian subcontinent, Atmos. Chem. Phys., 19, 11865–11886, https://doi.org/10.5194/acp-19-11865- 2019, 2019.

Pandey, S.K., Vinoj, V., Landu, K. *et al.* Declining pre-monsoon dust loading over South Asia: Signature of a changing regional climate. *Sci Rep* 7, 16062 (2017).

Prabha T.V., Khain A., Maheshkumar R.S., Pandithurai G., Kulkarni J.R., Goswami B.N. (2011), Microphysics of Premonsoon and Monsoon Clouds as Seen from In Situ Measurements during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), J. Atm.Sc., Vol.68, 2011, DOI:10.1175/2011JAS3707.1,1882-1901.

Rao, P. S. 2005 Arabian Sea monsoon experiment: An overview. *Mausam*, 56, 1– 6

Réveillet, M., Dumont, M., Gascoin, S. *et al.* Black carbon and dust alter the response of mountain snow cover under climate change. *Nat Commun* 13, 5279 (2022). https://doi.org/10.1038/s41467-022-32501-y

S. K. Satheesh, 2002, Aerosol Radiative Forcing by Indian Ocean Aerosols: Effect of Cloud and Surface Reflection, Annales Geophysicae, 20, 2105-2109

Satheesh, S. K., Torres, O., Remer, L. A., Babu, S. S., Vinoj, V., Eck, T. F., Kleidman, R. G., and Holben, B. N.: Improved assessment of aerosol absorption using OMI-MODIS joint retrieval, J. Geophys. Res.-Atmos., 114, D05209, https://doi.org/10.1029/2008JD011024, 2009.

Sorooshian A, Feingold G, Lebsock MD, Jiang H, Stephens GL (2009) On the precipitation susceptibility of clouds to aerosol perturbations. Geophys Res Lett 36(13):L13803. https://doi.org/10.1029/2009GL038993

Twomey, S. The influence of pollution on the shortwave albedo of clouds. J. Atmos. Sci. 34, 1149–1152 (1977).

Vinoj, V. and Satyendra Kumar Pandey. "Role of meteorology in atmospheric aerosols and air pollution over South Asia." *Asian Atmospheric Pollution* (2022)

Welton, E.J., S.A. Stewart, J.R. Lewis, L.R. Belcher, J.R. Campbell, and S. Lolli, 2018. Status of the NASA Micro Pulse Lidar Network (MPLNET): Overview of the network and future plans, new Version 3 data products, and the polarized MPL. EPJ Web of Conferences, 176, https://doi.org/10.1051/epjconf/201817609003

Xu, H. et al. Warming effect of dust aerosols modulated by overlapping clouds below. *Atmos. Environ.* 166, 393–402 (2017).

CHAPTER 5: EXTREME EVENTS

Sandeep Pattnaik and Vimal Mishra

Coordinating Lead Author
Prof. Sandeep Pattnaik, IIT Bhubaneshwar

Lead Author
Prof. Vimal Mishra, IIT Gandhinagar

BACKGROUND

Climate change and extreme weather events in India are becoming increasingly common owing to the rapidly changing weather patterns. As global warming continues to rise, regional climates are slowly transforming, leading to an increased frequency of intense weather events in India. With an influx of floods, droughts, and tropical and heat waves, the country is being forced to learn how to better adapt to the rapidly changing climate to mitigate the economic, environmental, and public health losses associated with extreme weather. The Indian subcontinent has been particularly hard-hit because of its large land mass, which is home to many vulnerable people and ecosystems. For example, over the past decade, India has seen major flooding events along its rivers, leading to mass displacement of people, and was hit particularly hard by Cyclone Amphan in 2020. India has experienced extreme temperatures, leading to an increase in heat-related illnesses and deaths. According to India's National Crime Records Bureau, over 1,700 people died of heat-related illnesses in 2019. In recent data released by India Meteorological Department (IMD) about 2227 deaths have occurred due to extreme weather conditions in India (State of the Climate 2022). Research has shown a correlation between climate change and extreme weather events, and it has become increasingly important to account for the potential hazards arising from increased temperatures. Recently, extreme weather events have caused serious damage to human lives, property, and livelihoods. Weather-related natural disasters, such as floods and tropical cyclone landfalls, can have devastating effects. Therefore, it is vital to understand the relationship between climate change and weather events and their associated long-term consequences and prepare accordingly.

India is a vast country that experiences a range of extreme weather events, such as floods, droughts, tropical cyclones, heat waves, and cold waves. These events were caused by several different environmental factors, including India's close proximity to the Indian Ocean, major rivers, and mountainous terrain. In climate change scenarios, there is a rapid increase in the frequency, intensity, and duration of extreme weather events around the world, including in India. For example, India has witnessed approximately 241 extreme weather events out of 273 days in 2022 (nearly every day in the first nine months), causing 887 and 783 deaths over central India and eastern and northeastern regions of India (India 2022). Recent research has found that approximately 46.1% of the mortality rate due to extreme weather events in India is attributed to floods, followed by 28.6% due to tropical cyclone land over the Indian region (Ray et al. 2021). They also found that due to effective disaster mitigation preparedness and mitigation strategies about 94% deaths that occurred due to tropical cyclones have been reduced in the past two decades; however, during the same period, mortality due to heat waves and lightning has been increased by 62.2 % and 52.8% respectively in India. Major states such as Odisha, Andhra Pradesh, Assam, Bihar, Kerala, and Maharashtra were found to be the most vulnerable states in the country affected by extreme weather events, emphasizing that better disaster planning and mitigation measures should be initiated in these states on priority. Floods are among the most common extreme weather events in India. The Indian monsoon season plays a significant role in this type of event, as heavy rainfall can lead to flash flooding and overflowing rivers. This can occur throughout the country, but certain areas are most at risk, such as Assam and the western Ganges River Basin. The most extreme floods of 2022 in Gujarat and Assam have led to the devastating loss of life, massive evacuations, and disruption of transportation and infrastructure. In addition, people living in coastal areas are particularly at risk and are highly vulnerable, as landfall cyclones can cause massive storm surges and inundation immensely impacting their lives and livelihoods. Heat and cold waves also occur in India, with the latter occurring mainly in the northern part of the country during winter. Heat waves, however, can be extremely dangerous, especially in areas such as the northern plains, where temperatures can reach 45°C or higher. These heat waves can cause dehydration, heat exhaustion, and heat stroke and can have a significant impact on public health.

The recurring menace of extreme weather events such as tropical cyclone landfalls, heavy rainfall, flash floods, floods, and landslides between 2006-2021 has caused a crop loss of 36 million hectares, leading to a loss of $3.75 billion USD to farmers and further, it is worth mentioning that about there is income loss of $159 billion USD (about 5.4% GDP) in the services, agriculture, manufacturing, and construction sectors due to extreme heat in 2021 (climate transparency report 2022). Therefore, the effective handling of extreme events requires a strategic, broader, and comprehensive approach that incorporates state-of-the-art knowledge and technology at the local scale. According to the IPCC, extreme events are rare at a particular place and time of the year and would normally be rare or rarer than a particular percentile (i.e., 1st, 5th, 10th, 90th, 95th, 99th) of the probability density function estimated from observations expressed as departures from daily or monthly means. As per the Indian Meteorological Department (IMD), a variety of extreme weather events have occurred over the Indian region, including heavy to very heavy to extremely heavy rainfall events, frequent landfall of intense tropical cyclones, cloud bursts, land slides and flood situations, heat waves, cold waves, dust and sandstorms, droughts, squalls, gales, hail storms, lightning, and thunderstorms. In addition, it is also evident that there is a distinct pattern of change in regional and global precipitation signatures, particularly with reference to the Indian monsoon under the global warming scenario. Goswami et al. (2006) noted that the shorter and more intense durations of rainfall episodes are on the rise compared to light to moderate rainfall events over the Indian region. Overall, India experiences a range of extreme weather events that can have devastating effects on the country's life, infrastructure, and economy. There are measures that can be taken to mitigate the effects of these events, such as early warning systems and improved early response plans, and the challenge for India is to adapt to these changes to prevent further damage. Therefore, the increase in intensity and frequency of extreme events highlights the need for immediate and sustainable climate action; however, in this report, we will discuss some of the actions countries should initiate to reduce the loss due to these events, particularly emphasizing a better scientific understanding of accurate early warning systems in order to create a resilient society and country in a longer time frame.

Key Objectives

The primary objectives are the following;

1. Create and maintain a long-term high-density sustainable data network for monitoring, archiving, and seamless exchange, particularly regarding localized extreme weather and climate events over the Indian region. This will create an excellent baseline for better scientific quantification of past and future events from an enhanced perspective in terms of scientific understanding and policy formulation. Hence, there is a massive investment in the deployment of state-of-the-art equipment (airborne, surface) for reliable and high-resolution observations.
2. Quantifying the attributes of key climate parameters, including anthropogenic contributions and key indicators triggering these location-specific extreme weather and climate events.
3. Improving our understanding to identify the key role played by important physical processes (i.e., clouds, boundary layer, and land surface) in regulating these extreme events. Grand specific challenges in cloud microphysics, boundary layer, and large-scale interactions through high-resolution modeling simulations for targeted region-specific extreme events, such as tropical cyclone landfalls, monsoon low-pressure systems, cloud bursts, orographically triggered heavy rainfall, thunderstorms, lightning, and droughts.
4. Augmenting the early warning system through focused customized modeling experiments for specific targeted extreme events, regions, and seasons. This is essential to test and improve the early warning system products, at least with a lead time of up to 72 hours.
5. Improving the interlinking and interdisciplinary approach to handling hydro-meteorological disasters and other extreme rainfall events highlight the need for a multi-dimensional approach for region-specific robust understanding and preparedness.
6. Local communities should develop and adapt the local climate adaptation plan (LCAP) for fast and effective coordination and dissemination of forecasting information up to the panchayat level in the local language and fine-scale monitoring for effective implementation, compliance, and feedback for further improvement. More thrust is required to reach remote locations in a time-bound manner.
7. Establishment of consortia of academicians, scientists, operational agencies, policy, and disaster managers nationwide for seam-less interactions towards development and long-term sustainable collection, archival, and dissemination of hydrometeorological data in near real-time, evolving strategies to improve the location-specific impact-based early warning systems, and continuous development of the state of the model for target-specific disasters at the highest possible spatiotemporal resolutions.

ROADMAP

Short-term (by 2030)

Mainly, there are six areas where short-term action should focus on observations, coherent data archival and real-time dissemination, region and specific modeling with the goal of improving early warning modeling framework, special focus on urban areas, seamless interactions among the scientific community, academics to policy and risk managers at the local level for effective preparedness and adaptation strategies, and development of awareness among common citizens for effective resilience.

In summary, comprehensive measures in terms of developing sustainable high-density observations, improving the location-specific tailor-made modeling approach, and bringing the scientific understanding to the concerned policy and disaster risk managers for the implementation of effective resilience and adaptive measures to minimize the loss of lives and property due to extreme weather events. Finally, a coordinated effort must be made by different stakeholders, such as scientists, policymakers, risk managers, local authorities, private and public stakeholders, funding agencies, and common citizens to adapt location-specific approaches for better preparedness and resilience. We discuss these priority areas in the following sections.

1. First, it is imperative that as long as we do not have adequate observations, it is extremely difficult for the scientific community to examine the accurate scientific interpretation of the region and season-specific extreme weather events and, in particular, attribute these events to a climate change regime. First, efforts must be made to unify the newly generated state-of-the-art datasets with available past datasets across India in a coherent manner, at least at the district scale. Further attempts should be made to make it at the block level and accessible to the research community through a user-friendly web-based platform. This will help the research community augment their understanding of these extreme events. In the context of acquiring observations, there are multiple priority areas that require immediate attention, such as acquiring surface and upper observations, particularly over vulnerable regions, and efforts must be made to fill the data devoid of remote areas in a gradual manner. A key area of focus for improving early warning weather forecasts largely depends on improving data collection and processing efforts. Such efforts require not only well-trained meteorologists but also access to accurate and timely data from well-placed sources. Improved data collection systems, such as citizen-provided data, along with higher levels of accuracy from new observation technologies, can help significantly. These valuable datasets will create an immensely valuable resource for a better understanding of the underlying weather-based processes in retrospective extreme weather events through improved tracking of atmospheric conditions and can provide better insight into future weather patterns. If one considers localized heavy rainfall events, particularly over coastal districts and high mountain terrain regions, more deployment and operationalization of remote sensing instruments such as radars, cloud radiometers, laser precipitation monitors, micro rain radar, ceilometers, microwave radiometers, wind lidars, and lightning detectors are essential to obtain first-hand information about the event. This includes massive upgradation through investments in modern radar and in situ observations, and satellite systems with massive digital intervention through location-specific computational and visualization technology. In addition to acquiring observations, it is also imperative that these observation datasets are operationalized and maintained in an automated, unified, and coherent manner to provide us with better clarity in connecting complex interactions between local-scale and large-scale atmospheric circulations. This calls for targeted setting up of urban observations in select cities, and designing city-specific weather forecast models. If the urban authorities cooperate and provide flood data and ground water data, it will be possible to even estimate floods in vulnerable zones in the cities using AI/Ml.In this regard, honest efforts should be made to make these observation stations state-of-the-art, sustainable, robust, and automated in the long-term high-density observation network with a high priority on vulnerable regions such as mountainous and coastal zones of India

2. Event, region, and season-specific modeling exercises are key for creating tailor-made forecasting systems targeting season-specific vulnerable areas in countries. The high-resolution numerical weather models used for predicting extreme weather events must be validated before they can be trusted. To do this, we need robust independent on-site observations to obtain accurate knowledge about the region, season, and event-specific model biases. Therefore, intense region-specific modeling exercises must be adapted not only using present weather datasets but also futuristic climate change scenarios. These seamless exercises are essential to characterize the differences or inconsistencies in the models and can help minimize these inconsistencies for reliable predictions of location-specific extreme weather events, such as tropical cyclone landfall, heavy rainfall, lightning, drought, and dust storms. These exercises will immensely help evolve tailor-made region-specific early warning systems, which will be the backbone for predicting extreme weather events. Furthermore, extreme rainfall events are caused due to various drivers such as SST warming, urbanization, etc. In addition, the interannual variability, such as a co-occurring ENSO (such as the Chennai 2015 event) or a strong IOD event can exacerbate the rainfall intensity. Very few studies have addressed these aspects. Whatever are available, are based on a single model. Understanding the relative role of drivers using multiple models and datasets will be beneficial.

3. Urban India is one of the most densely populated regions in the world and has experienced drastic changes in its climate patterns over the last few years. With climate change, urban India has been subject to increasing frequency and intensity of extreme weather events, which have had serious impacts on both urban infrastructure and citizens with recent examples are Delhi (2021), Bangalore (2022), Hyderabad (2019, 2021), Chennai (2015), Mumbai (2015), Kolkata (2020) and many others. The major extreme events affecting urban India are tropical cyclone landfall, heavy rainfall, urban flooding, heat waves, and dust storms. Flooding is one of the most prominent extreme weather events occurring in urban India. India is a tropical country, and during the monsoon season, it faces heavy downpours that can lead to flooding, particularly in urban areas. Floods in urban India can cause extensive damage to property, homes, and public infrastructure such as roads and rail lines. In addition, flooding can lead to clean water supply shortages, putting citizens' health in danger. Heatwave events can be very damaging, as extreme heat with intense urban island effects can cause dehydration, heat exhaustion, and heat stroke, especially in the elderly and children. Moreover, excessive heat can interfere with the functioning of public transportation services, such as buses and trains, thereby disrupting the daily lives of citizens. In addition, high temperatures can increase the risk of fires, destroy urban properties, and cause long-term health issues due to air pollution. Urban India is also at risk of drought owing to climate change. Droughts can cause crop damage and water shortages in urban areas, leading to food and nutrition insecurity. These intense drought conditions can also lead to water contamination due to the over-extraction of groundwater, endangering the health of citizens. Furthermore, dust storms have become increasingly frequent in urban India owing to climate change. These storms, which can last for hours, are very dangerous because they can reduce visibility on roads, leading to car accidents and other traffic-related hazards. Haboob storms can also cause health issues ranging from skin and eye irritation to respiratory diseases.

In the short term, urban Indian cities need to follow measures to reduce the devastating impact of extreme weather events due to climate change in the coming years. One key step is irrespective of sectors (i.e., transport, road, housing, storm drainage, industry, etc.), which ensures that city infrastructure is designed in such a way that it minimizes the negative consequences of extreme weather events. Cities should adopt flood-proofing measures such as the installation of high-capacity pumps, floodwalls, levees, and other such systems, both along rivers and in urban areas. Moreover, cities should ensure that their drainage systems are well maintained and able to cope with increased volumes of water following extreme weather events. Good drainage systems will help prevent local flooding and reduce the impacts of cyclones and storms, as well as curb the potential for waterborne diseases in the aftermath of such events. Our cities must re-examine the unauthorized development of slums in climate-vulnerable zones, and existing slums historically impacted by extreme weather events must have retrofit measures to minimize the damage in future events or properly rehabilitate these vulnerable sections of society from the present location to an appropriate safe zone. Furthermore, citizens and local authorities of the city should take responsibility for planned and massive urban afforestation to develop natural canopies and reduce the impact of heat stress conditions. In line with this aspect, our cities should rejuvenate deplorable water bodies and create more water bodies to minimize the intense heat impact on their citizens from severe heatwave conditions. Our cities must create natural sponges by reducing concrete jungles and allowing our soil to be bare and open for water percolation and facilitating groundwater conditions.

In addition to the physical infrastructure, Indian cities should also consider massive investments to improve early warning systems. These would be invaluable in alerting citizens to impending extreme weather events and allowing people to take appropriate precautions to reduce their vulnerability. Furthermore, cities should invest in public education campaigns that raise awareness of the potential consequences associated with weather events and the steps that can be taken to limit their impact. Finally, cities should consider investing in insurance schemes to help protect those most at risk of suffering losses from extreme weather events. This could give people who suffer the consequences of such events a financial lifeline to help them recover their losses. Overall, emerging mega cities in India can take various steps to reduce their vulnerability to extreme weather events in the coming days. By investing in better infrastructure, early warning systems, public education campaigns, and insurance schemes, cities can ensure that their inhabitants are better equipped to withstand the impacts of extreme weather events, recover from them, and minimize losses.

4. As extreme weather events, such as cyclones, floods, and droughts, become more frequent and intense, adapting to these unpredictable events is critical to ensuring the safety and well-being of local communities. A local climate adaptation plan (LCAP) is a proactive approach to preparing for and responding to these types of extreme weather events. By understanding the potential impacts of extreme weather, communities can reduce losses, mitigate risks, and develop effective strategies to cushion the impacts of major weather events.

   The first step in creating an LCAP is to assess the vulnerability of an area to extreme weather. This includes understanding the frequency and intensity of extreme weather events, as well as their potential impacts. The assessment should also consider socio-economic stressors, such as poverty, aging infrastructure, and population growth, which can make a community more vulnerable. Once a community's risks are understood, the next step is to develop and prioritize adaptation strategies. Adaptation measures should aim to reduce the impact of extreme weather events in both natural and built environments. This can be achieved through land-use planning as well as structural and non-structural measures. Examples of structural measures include hardening infrastructure such as strengthening communication networks and constructing seawalls, while non-structural measures such as community education, awareness programs, and early warning systems can also be useful. It is important to develop strategies tailored to the region that can be adapted over time as the needs of the community change. Once these measures are in place, the community must be prepared to respond to extreme weather conditions. This includes an effective communication plan, access to emergency services, evacuation plans, and shelter plans. Preparation and response should also include recovery strategies to restore the community as quickly as possible to the pre-event conditions. Ultimately, LCAP is a valuable tool for building resilience to weather events. By understanding the potential risks and developing strategies to address them, communities can better protect both their people and their environment and ensure that they are better prepared for any extreme weather event that may come their way. LCAP plans are tailored by a municipality or state to deal with the impacts of a changing climate in a particular area. These plans assess a given region's vulnerability to climate-related risks, outline combined public/private strategies to raise resilience, choose long-term adaptation strategies, and develop policies and draft legislation to ensure the sustainability of the local climate. A detailed and comprehensive LCAP can assist a municipality or state in preparing and adapting to an array of climate-related risks.

The primary goal of an LCAP is to identify existing climate-related risks and develop strategies to address these potential threats. Climate data must be analyzed to better understand the potential severity of climate-related risks in a given area, such as extreme heat, heavy rain, flooding, and storms. Second, stakeholders must come together to discuss best practices to prepare for such events and identify adaptation measures to reduce risks and potential damage to the environment and/or economy. Adaptation measures might include public education and awareness campaigns, conservation and management of natural resources, or changes to policies or land-use regulations. For instance, an LCAP can help guide the installation of green infrastructure, such as tree planting, rainwater harvesting systems, and stormwater retention ponds, which can improve water quality and reduce flood risks. Additionally, LCAP can be used to develop zoning or building regulations that adapt to current and future climate risks, such as increasing building codes for floodplains, green roofs, and flood-resistant zoning.

Developing an LCAP can also provide economic and environmental benefits by protecting assets, preserving the existing infrastructure and resources, reducing recovery costs after extreme weather events, and increasing the attractiveness of cities and regions. Institutions such as businesses, local governments, and emergency services can use this plan to build partnerships and share resources to help with emergency response and disaster recovery. Overall, LCAP is beneficial for municipalities and states to equip themselves with knowledge and strategies for preparing for and adapting to climate-related risks. By acting proactively, local governments can protect their economies, assets, and resources and ensure sustained prosperity in a changing climate.

5. Beyond this, governments should also find ways to enable better and more effective information sharing between regional meteorological offices and local disaster risk managers. By doing so,

more accurate and timely weather warnings can be delivered to the public in user-friendly language and means. Additionally, corporations and government agencies should also invest more in research and improved analysis tools for location-specific applications. By investing in advanced tools and software, information can be better analyzed, processed, and transmitted for region-specific purposes.

Finally, again reiterates that deployment of observation sensors, improving observational data collection/dissemination and effective outcome of early warning forecasts require the involvement of citizens. Citizens need to be made aware of their local warnings, and how to best prepare themselves during inclement extreme weather conditions. We should all remember that a precision weather forecast is one of the major components of disaster management but it is not all. Effective disaster management from extreme weather events also depends on effective communication, timely and targeted dissemination, strategic planning, and coordination among different stakeholders such as weather forecasting agencies, policymakers, risk managers, hospitals, non-government organizations, first responders, and local authorities. Finally, common citizens should learn how to recognize the signs of changing weather patterns, and stay informed of the latest warnings being issued. This can help protect them in times of emergency, and tighten the bond between the weather service and the citizens.

Long-Term (Beyond 2030)

Long-term adaptation to extreme events in climate change is essential to ensure the survival of humans, plants, and animals. As the planet warms, temperatures are predicted to rise more and more, meaning that extreme weather events will become more frequent, such as long periods of drought, severe heat waves, unseasonal rainfall, and stronger tropical cyclone landfalls. These events could bring about a range of disastrous consequences, from extreme food shortages and catastrophic damage to infrastructure to the displacement of communities and the endangerment of human lives. In this section broadly we have discussed three areas for long-term anticipatory planning and strategies such as reducing the emission of greenhouse gas (GHG) at the local level, continuous and proper risk assessment and management, tailormade location-specific adaptation strategies through rigorous scientific modeling exercises to understand the region-specific vulnerability and forecasting skills of the model.

Adaptation strategies for extreme events can involve a range of proactive approaches, such as anticipatory long-term planning and risk management. Long-term anticipatory planning at the local level involves local authorities, regional governments, and communities assessing their vulnerability to climate change and the impact of extreme weather events and identifying effective strategies for coping with its potential impacts. This includes developing plans to lower the greenhouse gas (GHG) emissions that lead to climate change, as well as improving the prediction capabilities for the targeted location and severity of extreme weather events. Additionally, investing in clean energy sources can help reduce GHG emissions, lowering the chance of future climate change-related catastrophes.

Risk management involves analyzing and evaluating the probability and consequences of climate change-related events, such as floods, tropical and droughts, and developing strategies to reduce their impact. There are also reactive approaches to long-term adaptation, such as developing protective infrastructure, natural barriers, and insurance schemes, as well as investing in green energy. Protecting infrastructure with floodproofing techniques or moving infrastructure away from at-risk areas can help mitigate the worst effects of extreme events such as heat waves, cold waves, the landfall of cyclones, droughts, and lightning. Climate change adaptation can only be successful if carried out in conjunction with a reduction in GHG emissions. The world has to reduce its carbon output in order to make sure that extreme weather events will not get worse. Adaptation strategies must also be tailored to fit the needs of specific communities, cultures, and locations, in order to make sure that every community can effectively brace for the climatic changes to come.

We need to understand the location-specific accurate mechanisms responsible for causing extreme weather and climate events and how this understanding can be better formulated in the models for an accurate prediction. In this context, region, location, and event-specific modeling exercises should be undertaken, to quantify the climate change-induced attribution to the occurrence of extreme events and their likelihood of its return period. These long-term assessments are essential to make our society and country better prepared and resilient to deal with extreme events. Therefore, long-term modeling and forecasting exercises particularly with a thrust on attribution assessment must be taken up by leading institutes and individuals to provide more scientific insight for improving early warning systems in the climate change regime, which is the backbone of future disaster mitigation and management activities. In this context, more thrust should be on the heavy rainfall events as they are least understood in terms of identifying credible land surface and hydro-meteorological drivers. For better attribution assessment long term, accurate and sustainable observations is a key component, hence massive efforts must be made on priority to fill this gap. Therefore, improving and customizing regional weather and climate models, observation density, and rigorous location and event-specific modeling and forecasting validation exercises including attribution assessment studies are essential ingredients for better interpretations of extreme weather events and for developing reliable early warning systems.

In developing nations, detrimental effects from extreme events are felt exasperated due to inadequate resources, infrastructure, and technological capability. As observed in the last two decades, floods and tropical storms induce more destruction and displacement of people in communities in developing countries; poverty, drought, and socio-economic weaknesses encourage this. Resilience is an essential factor for surmounting extreme events in these areas; building disaster-resilient infrastructure, installing early warning systems, and introducing proactive risk management systems can help combat normal fluctuations of natural hazards. Humankind is vastly dependent on its environment, and the consequences of extreme events such as hazardous temperature spikes, severe weather conditions, and intense floods can have a drastic impact on communities and cultures alike. In a holistic approach, preparedness is key in facing these natural events. Long-term adaptation to extreme events is necessary in order to mitigate potential risks and constructively respond to events that cannot be avoided.

However, the presence of risk is inevitable. With climate change and its effects compounding the already existing risks present in vulnerable communities, adaptation strategies need to form the core of comprehensive approaches to combating extreme events. Further, in a long term, effective urban planning through massive plantations and afforestation measures are essential to provide shade and store less heat in concrete by reducing ambient temperature and resulting in better management of urban heat island effects, particularly during intense heat wave conditions. Therefore, long-term adaptation strategies should include surge protection devices, introducing measures to manage high-intensity rains, ensuring health posts are constructed above flooding lines, preserving and protecting water sources, restoring coastal wetlands, and promoting environmental awareness campaigns. Allowing communities to be proactive and provide advanced, effective plans can aid in reducing the potential destruction caused by extreme events.

At a broader scale, leaders and decision-makers should employ long-term adaptation of extreme events to secure the livelihoods of future generations and ensure safe and secure societies for all. A comprehensive approach involving better early warning systems, integrated strategies for advance planning, introducing socio-economic policies, and incorporating traditional knowledge of local communities can improve the adaptability of vulnerable populations. Additionally, mechanisms for financial assistance from local and international partners can fill the gaps in adaptation needs by aiding vulnerable communities to aid in mitigating and preparing for extreme events. At the very heart, the strategy of preparedness needs to be emphasized to improve the chances of a constructive response to extreme events and achieve long-term adaptation. Schools and universities can play an important role by introducing and spreading information on risk management principles, encouraging the use of technology for communications, and making hygiene and sanitation an integral component of the curriculum to better promote the overall long-term adaptation of extreme events. On the educational side, we should have large investments in awareness and training programs to build individual and community-level capacity to prepare for and respond to extreme weather. These programs must have focused on education and training on the impacts of climate change, and adaptation strategies toward minimizing the impact of extreme weather events. traditional mitigation practices, and the potential of renewable energy sources.

Though the Indian government has recognized the importance of adaptation in order to manage the impacts of climate change, adaptation has been lagging behind. We should integrate of local climate adaptation plans with country climate adaptation plans for the implementation of a variety of adaptation strategies, ranging from technological and infrastructure-based solutions to educational programs. In terms of infrastructure-based solutions, we need to build numerous multi-hazard shelters (i.e. lightning, floods, cyclones), local dams, and embankments along rivers and coasts in order to protect against floods and cyclones. India also needs to invest large amounts in improving the early warning systems and flood forecasting to help reduce impacts from extreme weather events.

Overall, India has taken steps to address the impacts of climate change, however, there is still much work to be done. As India continues to experience more frequent and intense extreme weather events, it is critical for the government to continue to invest in adaptation strategies in order to better manage the economic, environmental, and public health losses associated with climate change. Long-term adaptation to extreme weather events in a changing climate is necessary in order to mitigate the worst effects of these events. Governments and communities need to work together to identify and implement proactive and reactive strategies, simultaneously reducing emissions to ensure the survival of humans, plants and animals in the future. In conclusion, facing the dangers of extreme events requires a multifaceted approach. Long-term adaptation is key in order to mitigate risks and respond constructively, which includes reforming infrastructure, identifying potential risks, introducing proactive strategies, and incorporating traditional knowledge to better fortify vulnerable communities. Thus, there is an urgent need to promote and implement proper resilience and long-term adaptation strategies in order to ensure safe and secure societies.

CHAPTER 6: URBAN CLIMATE

Rajesh Kumar Mall, Subimal Ghosh and Akhilesh Gupta

Coordinating Lead Author
Prof. Rajesh Kumar Mall, Banaras Hindu University, Varanasi

Lead Authors
Prof. Subimal Ghosh, IIT Bombay
Dr. Akhilesh Gupta, Science and Engineering Research Board

BACKGROUND

Anthropogenic greenhouse gases (GHGs) emissions have resulted in global warming which is widespread, rapid, and intensifying, and unprecedented in thousands of years (IPCC, 2013, 2021). IPCC AR6, WG1 assessed with a high confidence that climate change is affecting every region of Earth, in multiple ways. The changes we experience is more likely to increase with further warming. Climate change is impacting and will continue to have its impact on cities' basic services, infrastructure, housing, human livelihoods, and public health, among others. At the same time, cities are a key contributor to the climate change, as urban activities are major sources of greenhouse gas emissions apart from the post-harvest agricultural-waste and bio-fuels burning emissions in rural areas. Estimates suggest that cities are responsible for 75 percent of global CO_2 emissions, with transport sector and energy consumption in buildings being the largest contributors. Globally, the cities and urban regions are facing the highest risk due to climate change associated hazards (IPCC, AR6, WG2, Ch 6, with a high confidence). The urban population of the world has grown rapidly from 751 million in 1950 to 4.2 billion in 2018. Asia, despite of its relatively lower level of urbanization, is home to 54% of the world's urban population, followed by Europe and Africa with 13% each. By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in developing regions. However, some of the fastest-growing urban agglomerations are cities with fewer than 1 million inhabitants, many of them are located in Asia and Africa. While one in eight people live in 33 megacities worldwide, close to half of the world's urban dwellers reside in much smaller settlements with fewer than 500,000 inhabitants (UN DESA, 2018). Urban regions have high vulnerability and exposure, which when are combined with climate extremes hazards, produce a very high risk. In low- and middle-income countries, having low adaptive capacities, the most of the urban growth is unplanned in the small and medium sized city centre. This changing pattern is adding a further severity on top of the already existing climate crisis & stress (IPCC, AR6, WG2, Ch6).

The IPCC AR6, WG2 assessed increase in human health and economic losses in the cities due to single, compound, cascading and systematic climate events, and revisits the findings from its AR5 with a high confidence. The climate adaption to such events further got impacted by COVID-19. The adaptive capacity of the cities in South Asia and Sub-Saharan Africa has been further reduced because the pandemic has pushed an additional 119 to 124 million people into extreme poverty in 2020. There is also a huge gap between the city adaptation planning and its actual implementation, as reported by the IPCC AR6. The UN projections indicate that 68% of the world population are going to live in urban areas by 2050. Hence, it is very likely that cities are going to witness a significant influence on construction and transportation—two of the key contributors to global warming emissions. Moreover, because of the processes that drive climate conflict and climate refugees, city areas are expected to grow during the next upcoming decades, stressing more on infrastructure and concentrating more impoverished people in, if not all certainly in some of the pockets of, the cities. Most of the cities are facing a large number of problems due to climate hazards i.e., extreme floods, deadly snowstorms, ice storms, heat waves, droughts, and hurricanes. In coming decades, hundreds of millions of people in urban areas are likely to be affected by the rising sea levels, increased precipitation, inland floods, more frequent and stronger cyclones and storms, and due to extended and intense periods of extreme heat waves and short duration though extreme events of cold waves. Air pollution and climate change are inextricably linked in terms of (i) emission sources, (ii) climate characteristics and chemistry, and (iii) mitigation measures. They both entail significant consequences for the public health. For instance, the particulate matter (PM) is not only associated with the adverse health impacts (Heal et al., 2012) but also have a circuitous climatic impact, as they can act as the cloud condensation nuclei and thus influence climate forcing as well as meteorological phenomena (Williams, 2012; Von Schneidemesser et al., 2015; Maione et al., 2016).

Although the climate change is a global phenomenon, its impacts are more localized and need to be tackled by mitigation of emissions of GHGs and black carbon through a globally coordinated and a nearly synchronized effort. Upgrading (as and when required) and adopting climate-adapted policies and planning of land use & urban development will have potential to substantially reduce damages driven by the changing climate. Furthermore, each city will have a distinct disparity towards vulnerability and adaptation measures which in turn emphasizes on the fact that cities should concentrate their efforts in mitigating the climate change and implement & follow-up adaption actions for the safety and benefits of its population from the aforementioned hazards.

The Indian scenario:

The *2018 Revision of World Urbanization Prospects,* produced by the Population Division of the UN Department of Economic and Social Affairs (UN DESA), reports that future increase in the size of the world's urban population is expected to be highly concentrated in just a few countries. India, China and Nigeria will account together for 35% of the projected world's urban population growth between 2018 and 2050. By 2050, it is projected that India will have additional 416 million urban dwellers, China 255 million and Nigeria 189 million.

India is the second largest urban system in the world with almost an 11% of the total global urban population living in Indian cities. In absolute numbers, the urban population in India is more than several highly urbanized countries/regions across the globe. The country has reached at a turning point in its journey of economic transformation wherein half of the country's landmass would be 'urban' through city expansion in a few decades. Urban population growth is expected to contribute to about 73% of the total population increase by 2036 (MoHFW, 2019).

Over the years, cities have been expanding and imposing burdens and stress as an aftermath of unplanned urbanization, the brunt of which is faced by all residents with more pronounced by the poor and the marginalized, in addition to the loss of biodiversity and economy. In fact, the Covid-19 revealed the urgent need for city-level planning and management across the nation, with an emphasis on smart health care facilities and management for all (Balakrishnan et al., 2019; Singh et al., 2019, 2021; Niti Aayog, 2021).

Major pieces of evidence of changes in Indian urban climate are as follows:

1. Temperature: For the past 120 years, the India Meteorological Department has made a thorough attempt to make a high-quality observation across India from over 1,000 monitoring stations. Based on these data, it has been reported that the annual mean surface air temperature in India increased by 0.6°C between 1901 and 2010 (Rajeevan and Nayak, 2017). The majority of the increase in temperature has occurred over the past 30 years with more conspicuous records observed during the pre-monsoon and winter seasons (Srinivasan, 2019). The change in mean temperature is primarily due to a long-term trend of rising daily maximum temperatures. Model prediction shows that by the end of 21st century, India is more likely to experience a rise in the surface air temperature having a magnitude ranging from 2 to 4°C (Srinivasan, 2019). Additionally, an increase of 0.6°C in the sea surface temperatures around Indian subcontinent have been reported during the past 50 years, with the largest increase seen around the equatorial Indian Ocean (Rajeevan and Nayak, 2017). Furthermore, the frequency and duration of heatwaves occurring during the summer (or pre-monsoon) season has been increasing with most of the increase being witnessed in the recent decades (Singh et al., 2021). The number of hotter days in India's west coast increased from two to twenty between 1970 and 2005 (Kothwale et al., 2010). Over the same annual-scale period (1970–2005), the number of colder days got decreased by ten days. Overall, the meteorological observational records show that the ambient near-surface temperatures have risen substantially in most of the India over the last century.

2. Precipitation: Kuttippurath et al. 2021 has observed significant changes in the rainfall in north-east India over 119 years (1901-2019) and confirmed a declining trend of approximately 0.42 ± 0.024 mm/decade. For example, Kerala has experienced a decline in rainfall over the last 50 years, which is attributable to global warming by some of the climate models (Rajeevan and Nayak, 2017; Rajendran and Kitoh, 2008). Furthermore, there has been a shift in the distribution of rainfall towards more extreme rainfall events (rainfall greater than 100 mm/day) with 50% increase in heavy precipitation events in Central India over the last 50 years (Goswami et al., 2006). This is also evident in Mumbai, one of India's megacities and home to the largest population at risk of coastal flooding (Intergovernmental Panel on Climate Change IPCC-SREX, 2012). The changes in rainfall pattern have amplified the cases of both the droughts and floods in India.

3. Sea-level rise: Coastal states in India, including West Bengal and Gujarat, are most vulnerable to the sea-level rise (Srinivasan, 2019). Annual sea-level rise of 2.5 to 3 mm along the Mumbai coastline has been reported (Pramanik, 2017). However, as with rainfall, sea-level rise is influenced by both the local as well as global factors, such as subsidence. For example, in Kolkata, sea-level has risen by 5.22 mm/year over the last 50 years (Unnikrishnan and Shankar, 2007).

4. Air pollution: One of the recently realized emerging threats to human health in Indian cities is resulting from the complex nexus of air pollution and climate change (Rajput et al., 2023). The increase in health problems is expected to keep on rising as the climate variability increases (Bush et al., 2011). According to the Lancet Commission, air pollution causes 9 million premature deaths worldwide each year (Watts et al., 2015). Knowledge on spatial distribution of $PM_{2.5}$ concentration

although has drastically increased through interpolation and modeling in the last several years, the availability of high-resolution ground-based $PM_{2.5}$ monitoring data is still a major concern. Moreover, source-apportionment of fine particulates has still not been carried out over most of the Indian cities incorporating molecular markers. This limits the fundamental understanding of air pollution and its sources in India. Some specific studies, especially over National capital Delhi and Kanpur has resulted in improved understanding of composition and sources of non-refractory (NR) organic aerosols and sources. Overall, vehicle emissions have been identified as the most common source of fine particulates and high NO_2 concentrations, followed by industries and fossil-fuel combustion, thereby increasing air pollution in India's urban areas (Mondal et al., 2000; Ghose et al., 2004; ARAI, 2010). In a study published by the National Environmental Engineering Research Institute (CPCB, 2010), open burning and landfill fires of municipal solid waste were identified as the leading sources of air pollution in Mumbai, India. Motor vehicles contribute 51.4% of air pollution in Kolkata, followed by industrial emissions at 24.5% and dust particles at 21.1%. (West Bengal Pollution Control Board, 2005). Increased population, urbanization, and industrialization have depleted air quality, which has a negative impact on human health (Rumana et al., 2014). The increase in air pollution has a variety of synergistic effects on climate change impacts. Furthermore, the effects of particulate matter, black carbon (BC), and organic compounds including polycyclic aromatic hydrocarbons (PAHs) on public health need to be studied more thoroughly.

5. Extreme Events: Urban areas in India is vulnerable to a wide range of climate risks, including coastal surges and cyclones (Sridhar, 2016), uneven precipitation causing water stress (Kumar et al., 2016), heat waves and rise in minimum temperatures (Dholakia et al., 2015; Rohini et al., 2016; Singh et al 2021), increased incidence of diseases such as malaria (Sahay, 2017), and an increase in the frequency and intensity of floods, storms, torrential rains, and droughts (Haines et al., 2006; Majra and Gur, 2009). Climate change projections for 57 Indian cities from 2036 to 2060 show that 33 cities are likely to experience increased extreme rainfall and a high risk of flood. The remaining 24 cities will see precipitation decreases, indicating a higher risk of drought (Ali et al., 2014; Singh et al., 2021). Furthermore, the total cloud cover during the monsoon period has decreased from 72% to 66% over the last 50 years, while the percentage affected by drought in India has increased from 10% to 20% between 1959 and 2009 (Rajeevan and Nayak, 2017). Cyclonic disturbances have decreased from seven per year in the mid-twentieth century to less than two per year in the last decade of the 20^{th} century (Dash et al., 2007). Because of the occurrences of Urban Heat Island (UHI), certain pockets of a city are expected to have a greater impact of climate extremes such as precipitation extremes or heat waves than the rural areas (Shepherd, 2005; Shastri et al., 2017; Chauhan and Singh, 2020, Singh et al., 2020). IPCC AR6 reported the following reasons behind the increase in heavy precipitation over the urban regions: (i) increase in atmospheric moisture content due to horizontal convergence of air associated with the UHI effect (Shastri et al., 2015; Argüeso et al., 2016); (ii) increases in cloud condensation due to urban aerosol emissions (Han et al., 2011; Sarangi et al., 2017); (iii) aerosol pollution that impacts cloud microphysics (Schmid and Niyogi, 2017); and (iv) urban structures that impede atmospheric motion (Shepherd, 2013; Ganeshan and Murtugudde, 2015; Paul et al., 2018). The extreme precipitation results into extreme flood because of almost no infiltration in an urban region. The sea-level rise will exacerbate the damage caused by storm surges during cyclone made landfall. Changes in rainfall patterns and surface temperature may have an impact on vector-borne diseases. In theory, rising

surface temperatures over the land will make more areas suitable for the spread of malaria and dengue diseases (Bhattacharya et al., 2006).

6. Urbanization, Infrastructure and Energy Sector: By 2050, an additional 400 million people are expected to live in Indian urban settings i.e., doubling in four decades from 2014. (UN DESA, 2014). Estimates indicate that two-thirds of India's built environment will be constructed between 2010 and 2030 to support this population and economic growth (Kumar et al., 2010). Such transitions put extraordinary strains on infrastructure and resources, though urbanization will be a key determinant of India's future development. India's urban concentrations are distinguished by a number of complex characteristics and diversified urban forms. This includes megacities such as the National Capital Region (NCR), Greater Mumbai, and Bangalore, to the many more small and medium-sized cities. As the urban population grows, the demand for basic services will increase, which in turn will raise the concerns about inclusivity and putting additional strain on already-strained resources and infrastructure. Rising income levels and greater access to basic services will result in the urban energy demand, particularly from transportation, residential, and industrial sectors (ICLEI- South Asia, 2009). Climate change also exacerbates social vulnerabilities. Thus, those in urban areas without adequate shelter, drainage, and water, as well as those with social disadvantages, will be the most affected ones (Hughes, 2013; Rumbach, 2018; Yenneti et al., 2016).

7. Urbanization brings changes in land-cover and land-use pattern over a region which ultimately leads to shift the ecological balance of the region, local energy budget and causing modification in urban climate. UHI effect over India has also been studied by many researchers considering the changes in surface albedo, modification in atmospheric temperature profiles and changes in local meteorology. The UHI has also been explored to effect the urban-rural gradients in surface temperature and other meteorological events like occurrence and persistence of fog. UHI effect has also studied against changes in aerosol and a significant negative correlation is reported for Delhi (Pandey et al., 2014). Besides, increase in urban sprawl, urban built-up/urban settlement areas also affect the comfort of living. The changes in land use and land cover over the urban region and consequent increase in urbanization has led to intensify UHI with specific effect on near-surface temperature and humidity level (Kedia et al., 2021).

   The widely realized greatest threat to life on Earth is the climate change. Air pollution triggers the climate change, among other factors, the sources of which can be both anthropogenic and natural but, especially those of greenhouse gases (GHGs) which have predominant contributions from human activities. Among many climate-change driven impacts, the anticipated increase in intensity and frequency of water and vector borne diseases, and human migration are to be among the top focuses of the public health management planning for the cities. Surely, many of these ongoing and ahead challenges associated with the changing climate are not new while their intensity and frequency remain largely uncertain in the future which demand for more concentrated approaches on urban planning and design sector. The major challenge towards tackling the urban climate change impact is the population explosion and urbanization as it contributed in making 2.8% of the planet's surface into a metropolitan region which is a home to more than 50% of the world's inhabitants as of 2008 (El Sioufi et al., 2010). Rapid urbanization primarily takes place in developing nations, where a significant demographic shift has a strong linkage, directly or indirectly, with the climate change. India's rate of urbanization has climbed by nearly 4% over the past ten years as more and more Indian’s relocate from the agricultural sector to the service sectors for employment and livelihood. This transformation of India will have significant effects on local welfare, environmental conditions, as well as climate actions (mitigation and adaptation). According to the United Nation Department of Economic and Social Affairs Social Inclusion (UN DESA), Population Division (2018); Up to 2030, India's top seven cities will grow even more. According to projections, Delhi, the capital of India, would have a population of 38.9 million during the next ten years, an increase of around one third.

Key Objectives

1. Understanding Urban Microclimate and improvement in high resolution modelling connecting scales associated with Direct Numerical Simulation (DNS), Large Eddy Simulations (LES) and Regional Modeling.
2. Strengthening Early Warning System and Forecasting of climate hazards to make cities disaster resilient.
3. Developing emission inventory for criteria air pollutants at a high resolution (at least, 1 km x 1 km).
4. Generating and assessing high resolution socio-economic and infrastructural vulnerability maps to understand the risk to climate change and impacts assessment.
5. Building Heat Resilience in the city through research on UHI (urban heat island) and heat action planning.
6. Urban planning and management with a focus on climate resilient urban infrastructure
7. Advancing research in public health modeling due to climate change and exposure to air pollution on different health outcomes.
8. Making cities sustainable and carbon neutral by reducing emissions and/or increasing carbon sequestration.
9. Improving co-ordination between research & policy to facilitate evidence-based policymaking.

ROADMAP

Management of urban climate change & scope for future research:

Cities are often regarded as a major source of GHGs and anthropogenic aerosols which drives long-term changes in climate patterns. Besides, cities are also the biggest consumer of the energy the demand of which is expected to keep on rising with the rise in ambient temperatures due to the climate change. Urban residents are also far more exposed to high levels of pollutants and witness negative consequences of climate change especially in terms of pluvial and river flooding, water borne diseases, human settlement and displacement, migration of population, lack of access to green space, among others. Thus, the major upcoming challenges of climate changing in urban management will be most possibly on handling the urban infrastructures especially on the drainage system, road transport, waste management, buildings and health system. Certainly, most of these challenges are not new but their complexity and nexus being exaggerated by rapid urbanization and climate change. Urban areas have huge potential and reasons to address the response of the climate change due to presence of a huge concentration of population, economic assets and financial framework, local governance which make urban areas an integral part of the solution. Mitigation and adaptation of climate stress lies well within the city by adopting a low-carbon based urban development plan and by safe-guarding urban population with climate resilient infrastructure. The major & specific aspects for the short-term (by 2030) and long-term goals (beyond 2030) of urban climate research must involve:

Short-term goals (by 2030)

1. **Climate resilient urban infrastructure and efficient resource management:** Anthropogenic emissions contributing to the GHG emissions as well as excess heat that exacerbates the impact of rising temperature. In such scenario, research and innovations in making urban infrastructure more climate and sustainable is the way forward for both immediate and long-term future. Research on increasing the use and efficiency of renewable sources of energy, shifting towards circular economy model of development, promotion of smart and energy efficient electricity system, optimizing resource consumption with minimum carbon footprint, climate smart transportation network etc. Near-term actions including climate smart interventions in urban planning and management. Recognize the roadmap of possible changes in population livelihood and energy practices to achieve carbon neutrality at the micro level.

3. **Strengthening Early Warning Systems and Forecasting:** With the rising extreme weather events and the scale of the damage caused, the role of efficient early warning systems has become more important than ever. In the short-term goal, it is essential to emphasize on strengthening the network of these warning systems so that it can protect everyone following the mandate of the World Meteorological Organization (WMO). The improvement in numerical weather prediction should focus on improved high-resolution forecasts increasing advanced forecasts period, coordination in its efficient dissemination of information will enable the response and relief to prevent any damages to the life and infrastructure. Developing effective climate information services based on the efficient forecasting and integrated knowledge network to address the need of urban population will require continuous research on the aspect. This will help in improved decision making and to achieve climate agenda 2030 of the sustainable development goals (SDGs).

4. **Desired Improvement in the Climate Model Simulations:** The trade-off between high resolution climate information, and time and computational requirements is still a big question and barrier in the regional climate projections. Predicting the effects of climate change at the district level is very desirable for informing and implementing adaptation policy and measures, but the methods to do so are still under the process of development. The changes in regional climate cannot be predicted with accuracy by the climate models used to project climate change for the twenty-first century. This is brought on by the high wavelength phenomena captured in the climate models and the gaps in our knowledge of Earth system science including but not limited to how the aerosols, clouds, and land use change affect local climate? In such scenarios, research in advancing the capacities of numerical weather prediction models as well as high resolution regional climate models in generating accurate regional climate information to be used for climate services must be on a top priority for India. While various global modeling experiments data are available for research an indigenously developed Indian regional climate model must be another major research focus for both short-term and long-term research goals in the country.

5. **Emission inventory of $PM_{2.5}$, PM_{10}, O_3, and NO_2 in the immediate future for vulnerable cities:** Understanding the sector specific emissions of both long-term and short-term climate stressors is the need of the hour to develop a city-specific emission reduction and management plan. There is a need for developing a high-resolution database of $PM_{2.5}$, O_3, and NO_2. Achieving this would require pooling of a lot of data sets from different sources including those from the India Central Pollution Control Board (CPCB) and performing statistical modeling to deduce a high-resolution mapping of air pollution over India. Research in building the pollution emission inventory and establishing a network for scientific analysis, simulation studies and forecasting of pollution exposure and climate change effects on diverse urban infrastructure would also be required. A comprehensive high-resolution emission inventory mapping over a city would enable in identifying hotspots of pollution sources.

6. **Advancing research in public health modeling due to short-term exposure to air pollution on different health outcomes**: Public health research providing strong evidence for linkage between short-term exposure to air pollution and mortality and other health outcomes/morbidity risks is the need of the hour. Studies on air pollution (AP) and cause-specific mortalities have not focused much for the heavy pollution regions in South Asia. AP and mortality risks have been studied in other parts of the world previously though at much lower concentrations than those observed herein over the northern India. Daily data of cause-specific mortality, air pollution (AP), and weather parameters need to be integrated in a way to understand the health effects of AP/extreme weather events. AP represents the third-highest risk factor for premature deaths in South Asia and responsible for around 11% of all-cause deaths (non-accidental) and 40 million disability-adjusted life years (IQAir, 2021). An interdisciplinary expertise and approach shall be required to better understand the health impacts of air pollution and climate events.

7. **Mapping and Monitoring of Urban Heat Island and its impact in cities**: Urban areas are most vulnerable to increasing heat waves and decreasing diurnal temperature range (DTR) (Mall et al., 2021; Singh et al., 2021). The land use and land cover changes and structural changes influence the micro-meteorology which give rise to the phenomenon of urban heat island (UHI) where the temperature over the cities/urban areas are higher as compared to the surrounding non-urban regions. Anthropogenic emissions, decreased green cover, shrinking natural water bodies with increasing air pollution load due to weak dispersion and rising nighttime temperatures altogether create a heat-health hazard for the inhabitant where air-pollution intensifies the condition. With rising global temperatures, the city inhabitants face dual threat of heat waves and urban heat island. Research based evidences show that these conditions contribute to impairment of thermoregulatory mechanism of the body and increases the mortality risk in people with comorbidity particularly older people with existing respiratory and cardiovascular issues. Under such scenario, it becomes necessary to understand UHI effect and thermal discomfort considering the change in land use/land cover pattern and by integrating local meteorology and air pollution effects. Considering the spatial heterogeneity, increasing the network of observational meteorological data collection, maybe through low-cost sensors, is required for UHI measurement and monitoring. Research focusing on remote sensing i.e., using high-resolution satellite products based UHI

observations is also required. Utilization of Indian satellite products for the monitoring of UHI is a thrust area that needs more research activities.

8. **Urban health, data repository, and heat action planning:** Urban climate and its impact on public health is an inter-sectoral research area that would require an interdisciplinary research approach and initiatives. While micro-climate research will aid in providing climate information, and developing a network of heat action plans for the cities that will reduce the impact of increasing heat waves episodes and UHI effect on the health of the inhabitants. While research on the association of climate extremes and increased incidence of vector-borne diseases are being carried out across the country, identifying the most vulnerable cities due to such risk in the near future using a high-resolution climate data through dynamic/statistical downscaling of regional climate models is required. However, health data is one of the major constraints in the field of urban climate and public health research. Hence, creating a holistic health database is the need of the hour that may involve collaborations and support from the Ministry of Health and Family Welfare (MoHFW) and healthcare professionals, among others for providing open access of health data to all researchers.

9. **Framing city specific adaptation strategies to mitigate the impact of climate change:** Based on varying vulnerabilities in a city to climate change, specific adaptation strategies need to be framed in the form of city adaptation plans and implemented accordingly. A continuous monitoring of adaptation actions and its effectiveness is also required to integrate in future urban projects.

10. **Urban Flood Modeling and Mapping:** Urban regions are severely affected by flooding; however, there are limited efforts resulted in generating full city scale urban flood models except for Chennai (Ghosh et al., 2019) followed by Mumbai (i-flow) and Bangalore. The Urban flood modelling is a challenging task considering multiple components associated with hydrologic modeling, hydraulic modelling, and input requirements such as spatially distributed rainfall information and DEM at a very high resolution. Most Indian cities do not have a proper observational flood monitoring system. There is a need to replicate the efforts made for Chennai and replicate for as many cities as possible by 2030s. Such models need to be connected to meteorological forecasting for real-time urban flood forecasting system.

Long-term goals (Beyond 2030)

1. **Making cities carbon neutral by the end of the century:** Cities across the world are aiming for carbon neutrality and so working through different networks to achieve so. Several states of the country have shown their commitment for the same for example Maharashtra has announced 43 cities to achieve zero carbon emissions by 2050. Developing and integrating the concept of climate neutrality in every upcoming urban developmental project by achieving net-zero emissions and by offsetting unavoidable emissions. Carbon neutral city network development to exchange scientific and policy ideas, and experiences among the community for addressing climate change at a larger-scale. Comprehensive analysis and development of an energy efficient and climate resilient water distribution system network is much needed across the nation.

Furthermore, a concentrated focus should include developing of an efficient collection and reuse of waste water to reduce stress on water resources.

2. **Advancing research in early warning systems and forecasting:** Application of artificial intelligence/machine learning in weather forecasting is an advancing field of research that has immense future scope. High-resolution climate information generation is a computationally expensive way that involves the use of complex algorithms and computations within fractions of time what we get today is the way forward for urban climate research in the long-term future. Also, monitoring of urban meteorology at a very high spatio-temporal resolution to understand the dynamics is highly required. Installation of multiple Radars in the cities could be the plausible solution for a better forecast system. Furthermore, there is an urgent need for developing high-resolution models for urban hydrology with a more robust and accurate numerical methods to integrate the new data products available in real-time.

3. **Micro-scale modeling for generating regional climate information:** The urban climate is changing at a fast pace and due to changing land-surface characteristics and its interaction with the atmosphere. Modeling this complex interaction to generate accurate regional weather and climate information is required to address the regional impacts of nexus of climate change and air pollution. More concentrated research on modeling the future climate at a micro scale considering high-resolution ground and satellite-based observations on emissions and micro-meteorology would be required. Thus, there is a high need to develop policies and integrate with urban developmental projects so that future scenarios may well be addressed.

4. **Emission inventory of criteria air pollutants and urban air quality management**: The rapid and unprecedented urbanization in India has tremendously increased the load of air pollution in regional context mainly due to increased vehicular emission and energy demand, and construction & demolition activities. We already have substantial contributions to air pollution from agricultural-waste burning and bio-fuels consumption from rural India. Mineral dust upliftment from the ground makes air pollution more critical during summertime (April to June).

5. **Health impact assessment due to long-term exposure to air pollution and temperature extremes:** Among the 17 SDGs, Climate Action represents Goal 13 and it's all about taking urgent actions to combat climate change and its impact globally, whereas Good Health and Well-Being represent Goal 3 (UN SDGs, 2022). Long-term data set of air pollution and weather parameters in addition to health outcomes records would be required for India to assess the health impact due to air pollution and temperature extremes. Studies on air pollution (AP) and cause-specific mortality have not focused much on heavy pollution regions in South Asia. AP and mortality risks have been studied in other parts of the world previously though at much lower concentrations than those observed herein over northern India. Daily data of cause-specific mortality, air pollution (AP), and weather parameters need to be integrated. Artificial intelligence/machine learning can be applied for advanced statistical analyses. AP represents the third-highest risk factor for premature deaths in South Asia and responsible for around 11% of all-cause deaths (non-accidental) and 40 million disability-adjusted life years (IQAir, 2021). Adaptation and mitigation strategies have been suggested particularly for South Asia to slow down the climate change and reduce the air pollution, and thus, reduce the associated mortalities (Hess et al., 2018; Knowlton et al., 2014). Furthermore,

changing climate is altering the patterns of precipitation and increasing the average temperature of the globe. This is altering the ecology of vectors and hence facilitating the spread of vector-borne infections over the new areas. In view of this, we would have to keep researching on the patterns and progress of non-communicable diseases (NCDs) in the context of climate change scenarios.

6. **Sustainable energy solutions & health benefits for cooking**: Lack of access to clean fuels and technologies starts at home. Women and children are exposed to polluted air when dirty fuels are used for cooking, as they spend their most time at home, and suffer additional risk while travelling. Accelerating access to clean cooking will not only save millions of lives, it will also reduce GHGs emissions and therefore protect our planet. Both research and policy-based interventions are needed for shifting towards green and clean cooking options in the prospective long-term particularly for the people from lower socio-economic backgrounds that are dependent on wood/solid fuels.

7. **Socio-economic impacts of climate change on cities**: Migration due to climate change is another major challenge in front of our country. While urban migration is common due to the lack of livelihood options, moving to urban regions due to climate change in form of coastal erosion, salt-water intrusion, submergence of agricultural land particularly in the islands is another emerging humanitarian issue. This field of research is still in development phase with least data availability. Hence, more focus and data-driven research on human migration due to consequence of climate change and its effect on the urban infrastructure is required. Urban population is already on the rise, these migrations will not only contribute to the population but the migrants may have to lead a poor and unhealthy life which is another area where policymakers need to look into it. Thus, a high-resolution socio-economic data generation in urban areas across the nation is the necessity of the hour.

8. **Disaster risk reduction, urban climate and governance for policy making**: Improved multi-level governance taking into account the latest scientific observations and understanding in policy decisions is the approach needed to be adopted for the changing climate. With rising frequency of extremes with disastrous impacts there is a need of disaster risk reduction planning at city level as they may suffer heavy consequences due to large population. Furthermore, comprehensive climate change adaptation and disaster risk management plans need to be developed for individual cities with a major focus on urban sustainability.

9. **Ease of access to urban climate data**: Efforts should be made for development of an open-source urban databases on supercomputing platforms which can be accessed by researchers, policy makers, municipal bodies, NGOs etc. This will not only accelerate the impact of climate on various outcomes but also help in capturing various phenomenon occurring in an urban agglomeration. This has implications to disaster risk management.

10. **Changing urban water cycles due to climate stressors**: Changes in precipitation, evaporation, and humidity have prolonged effects on the hydrologic cycle. However, in addition to the meteorological factors, the urban water cycle is also influenced by land use patterns, surface runoff, piped water delivery, and sanitation practices (Rohilla et al., 2017). The gradual intensification of the water cycle due to the present accelerated scenario in evaporation and precipitation has become one of the major

worries due to its significant socioeconomic effects across the globe. The intensification will generally make dry regions drier and wet ones more humid. The "National Water Mission" was launched in 2002 as a component of the National Action Plan on Climate Change to control and limit the detrimental impact of climatic changes on India's water resources (NWM, 2012). Basin-level management solutions for sustainability were a strong focus of the National Water Policy and efforts were made to build a water-efficient infrastructure that would increase water consumption by 20% (NWM, 2012). Afterward, the governmental initiative was launched through the Jal Shakti Abhiyan by the Ministry of Jal Shakti in 2019 to endorse water conservation at the grassroots level. Niti Aayog also investigated and reported 30 Indian cities are likely to face severe water deficiency in the future decades and 40% of the population can have a scarcity of drinking water by 2030 (NITI Aayog, 2021). About 72% of the districts in Maharashtra are already hit by drought, and its residents depend on water tankers. Owing to the lack of access to safe drinking water in India, at least 600 million people will have no/significantly less access to water (Niti Aayog, 2018). Central Public Health and Environmental Engineering Organization (CPHEEO) reported the increasing disparity between the demand and supply of water resources. Urban local bodies reportedly receive 69 liters of water per person per day on average (LPCD) which is far less than the recommended service level of 135 LPCD for domestic water use (CPHEEO, 2013). With the increasing population, the per capita availability of fresh water is expected to drop to 1000 m^3 by 2025.

The retreat of glaciers in the Himalayas and the Indian monsoon is becoming more inconstant, directly impacting water reserves. Increased rate of snow melt results in more precipitation and facilitates flood and water-logged situations as the rapid urbanization reduces the scope of infiltration to the ground and restricts the replenishment of groundwater reserves. Eventually, it results in a decline in water level and causes water shortages in urban areas. Furthermore, some regions in India experience less precipitation and are likely to face more prolonged periods of severe drought. The groundwater need will then increase and ultimately raises the water demands. The near future water stress is mostly related to rapid urbanization expansion in India (2.4 %) (Taenzler et al., 2011). However, the rights to utilize surface water and groundwater are ambiguous and state-specific. The state-level organization or local level mainly regulates water supply in the cities. At the local level, water supply mainly accesses water from human-made tanks (Taenzler et al., 2011) for domestic uses. However, middle-class families and sometimes poor-class families rely on household supplies received twice a day, but erratic water supply on hot summer days raises extensive water scarcity. Recently massive groundwater dependency has been observed in the local level urban population to meet the drinking and domestic needs. The distressing situation was exhibited when Chennai's civic authorities declared 'Day Zero' after the city's water supply ran out and the reservoirs dried up, garnering national and worldwide attention in 2019.

Besides, an estimated 10 crore liters of wastewater produced daily by a city with a population of around 3 million (CPHEEO, 2013), uncontrolled urbanization fetches up improper sewage collection into many wastewater pools, and untreated land disposals contribute to chemical contaminants in both surface and groundwaters. Hence, the demands of India's citizens regarding sanitation, safety, and health would be impacted by the continued degradation of its water supplies. Nationwide water conservation campaigns encouraged national participation like Jal Shakti Abhiyan to improve sustainability. The projects stress the methods, including inter-basin and intra-basin transfers, artificial groundwater recharge, desalination, rainwater harvesting, and awareness program to overcome adversity. Management practices should enhance by introducing alternative new sources of water. Water harvesting of rooftop rainwater, stormwater, atmospheric water generation, desalinated water, segregation, and differential treatment of black and grey water seems to be implemented urgently to ensure the sustainability and augmentation of the water reserves. These issues will require new scientific outlooks to be developed with innovative modeling tools. Digital twins of city-specific urban water systems need to be developed too.

REFERENCES

Ali, H., Mishra, V. and Pai, D.S., 2014. Observed and projected urban extreme rainfall events in India. *Journal of Geophysical Research: Atmospheres*, *119*(22), pp.12-621.

ARAI, 2010. Air Quality Monitoring and Emission Source Apportionment Study for City of Pune. Pune: The Automotive Research Association of India, [ARAI/IOCLAQM/R-12/2009-10]. Retrieved from: https://www.mpcb.gov. in/sites/default/files/focus-area-reports-documents/pune_report_cpcb.pdf (accessed April 15, 2021).

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R. S., Brauer, M., Cohen, A. J., ... & Dandona, L. (2019). The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. *The Lancet Planetary Health*, *3*(1), e26-e39.

Bhattacharya, S., Sharma, C., Dhiman, R.C. and Mitra, A.P., 2006. Climate change and malaria in India. *Current science*, *90*(3), pp.369-375.

Bush, K.F., Luber, G., Kotha, S.R., Dhaliwal, R.S., Kapil, V., Pascual, M., Brown, D.G., Frumkin, H., Dhiman, R.C., Hess, J. and Wilson, M.L., 2011. Impacts of climate change on public health in India: future research directions. *Environmental Health Perspectives*, *119*(6), pp.765-770.

Chauhan, A. and Singh, R.P., 2020. Decline in PM2. 5 concentrations over major cities around the world associated with COVID-19. *Environmental research*, *187*, p.109634.

CPCB, 2010. Air Quality Assessment, Emissions Inventory and Source Apportionment Studies. Mumbai. Central Pollution Control Board. Retrieved from: https://www.mpcb.gov.in/sites/default/files/focus-area-reports-documents/Mumbai_report_cpcb.pdf (accessed April 15, 2021).

CPHEEO, 2013, Advisory on Conservation and Restoration of Water Bodies in Urban Areas, Central Public Health and Environmental Engineering Organization, Ministry of Urban Development, Government of India, http://moud.gov.in

Dash, S.K., Jenamani, R.K., Kalsi, S.R. and Panda, S.K., 2007. Some evidence of climate change in twentieth-century India. *Climatic change*, *85*(3), pp.299-321.

Dholakia, H.H., Mishra, V. and Garg, A., 2015. Predicted increases in heat related mortality under climate change in urban India.

El Sioufi, M., 2010. Climate change and sustainable cities: major challenges facing cities and urban settlements in the coming decades. United Nations Human Settlement Programme (UN-HABITAT).

Ghosh, S., Karmakar, S., Saha, A., et al., 2019. Development of India's first integrated expert urban flood forecasting system for Chennai. *Current Science*, *117*(5), pp.741-745.

Ghose, M.K., Paul, R. and Banerjee, S.K., 2004. Assessment of the impacts of vehicular emissions on urban air quality and its management in Indian context: the case of Kolkata (Calcutta). *Environmental Science & Policy*, *7*(4), pp.345-351.

Haines, A., Kovats, R.S., Campbell-Lendrum, D. and Corvalán, C., 2006. Climate change and human health: impacts, vulnerability, and mitigation. *The Lancet*, *367*(9528), pp.2101-2109.

Hess, J. J., LM, S., Knowlton, K., Saha, S., Dutta, P., Ganguly, P., et al. (2018). Building Resilience to Climate Change: Pilot Evaluation of the Impact of India's First Heat Action Plan on All-Cause Mortality. *Journal of Environmental and Public Health*, *2018*, 7973519. https://doi.org/10.1155/2018/7973519 https://world101.cfr.org/global-era-issues/climate-change/how-do-governments-combat-climate-change

https://www.unep.org/explore-topics/energy/what-we-do/transport

https://www.urbanet.info/urbanisation-in-india-infographics/

Hughes, S., 2013. Justice in urban climate change adaptation: criteria and application to Delhi. *Ecology and Society*, *18*(4).

ICLEI-South Asia, 2009. Energy and Carbon Emissions Profi les of 54 South Asian Cities, British High Commission, New Delhi, India.

Intergovernmental Panel on Climate Change IPCC-SREX (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. a special report of working groups I and II of the Intergovernmental panel on climate change. in Field, eds C. B. V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. (Cambridge, New York, NY: Cambridge University Press), 1–582.

IQAir. (2021). World Air Quality Report, Region & City PM2.5 Ranking. Retrieved from https://www.iqair.com/world-air-quality-report

Kothawale, D.R., Revadekar, J.V. and Rupa Kumar, K., 2010. Recent trends in pre-monsoon daily temperature extremes over India. *Journal of earth system science*, *119*(1), pp.51-65.

Knowlton, K., Kulkarni, S. P., Azhar, G. S., Mavalankar, D., Jaiswal, A., Connolly, M., et al. (2014). Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India). *International Journal of Environmental Research and Public Health*, *11*(4), 3473–3492. https://doi.org/10.3390/ijerph110403473

Kumar, P., Geneletti, D. and Nagendra, H., 2016. Spatial assessment of climate change vulnerability at city scale: A study in Bangalore, India. *Land Use Policy*, *58*, pp.514-532.

Kumar, Satish, Kapoor R., Rewal R., Seth S., and Walia A., 2010. Developing an Energy Conservation Building Code Implementation Strategy in India, USAID India, New Delhi.

Kuttippurath, J., Murasingh, S., Stott, P.A., Sarojini, B.B., Jha, M.K., Kumar, P., Nair, P.J., Varikoden, H., Raj, S., Francis, P.A. and Pandey, P.C., 2021. Observed rainfall changes in the past century (1901–2019) over the wettest place on Earth. *Environmental Research Letters*, *16*(2), p.024018.

Maji, K.J., Dikshit, A.K. and Deshpande, A., 2016. Human health risk assessment due to air pollution in 10 urban cities in Maharashtra, India. *Cogent Environmental Science*, *2*(1), p.1193110.

Majra, J.P. and Gur, A., 2009. Climate change and health: Why should India be concerned?. *Indian journal of occupational and environmental medicine*, *13*(1), p.11.

Mall, R.K., Chaturvedi, M., Singh, N., Bhatla, R., Singh, R.S., Gupta. A., Niyogi, D. (2021). Evidence of asymmetric change in diurnal temperature range in recent decades over different agro-climatic zones of India. Int J Climatol. 2021;1-14. doi.org/10.1002/joc.6978

Mondal, R., Sen, G.K., Chatterjee, M., Sen, B.K. and Sen, S., 2000. Ground-level concentration of nitrogen oxides (NOx) at some traffic intersection points in Calcutta. *Atmospheric Environment*, *34*(4), pp.629-633.

NITI Aayog (2021). Reforms in urban planning capacity in India, Government of India, Retrieved from: https://niti.gov.in/documents/reports?page=4.

Niti Aayog (2022) https://www.niti.gov.in/sites/default/files/2021-09/UrbanPlanningCapacity-in-India-16092021.pdf

NWM (National Water Mission) (2012) National Water Mission under National Action Plan on Climate Change, comprehensive Mission Document, Available at official website: http://wrmin.nic.in

Pramanik, M.K., 2017. Impacts of predicted sea level rise on land use/land cover categories of the adjacent coastal areas of Mumbai megacity, India. *Environment, Development and Sustainability*, *19*(4), pp.1343-1366.

Rajeevan, M.N. and Nayak, S. eds., 2017. *Observed climate variability and change over the Indian region*. Springer.

Rajendran, K. and Kitoh, A., 2008. Indian summer monsoon in future climate projection by a super high-resolution global model. *Current Science*, pp.1560-1569.

Rajput, P., Singh, S., Singh, T.B., Mall R.K., 2023. The nexus between climate change and public health: a global overview with perspectives for Indian cities. *Arabian Journal of Geosciences* 16, 15. https://doi.org/10.1007/s12517-022-11099-x

Rohilla, S. K., Matto, M., Jainer, S., Kumar M., Sharda, C., 2017. Policy Paper on Water Efficiency and Conservation in Urban India, Centre for Science and Environment, New Delhi.

Rumana, H.S., Sharma, R.C., Beniwal, V. and Sharma, A.K., 2014. A retrospective approach to assess human health risks associated with growing air pollution in urbanized area of Thar Desert, western Rajasthan, India. *Journal of Environmental Health Science and Engineering*, *12*(1), pp.1-9.

Rumbach, A., 2017. At the roots of urban disasters: Planning and uneven geographies of risk in Kolkata, India. *Journal of Urban Affairs*, *39*(6), pp.783-799.

Sahay, S., 2018. Urban adaptation to climate sensitive health effect: Evaluation of coping strategies for dengue in Delhi, India. *Sustainable cities and society*, *37*, pp.178-188.

Shastri, H., Barik, B., Ghosh, S., Venkataraman, C. and Sadavarte, P., 2017. Flip flop of day-night and summer-winter surface urban heat island intensity in India. *Scientific reports*, *7*(1), pp.1-8.

Shepherd, J.M., 2005. A review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interactions, 9(12), pp.1-27.

Singh, N., Mhawish, A., Ghosh, S., Banerjee, T., & Mall, R. K. (2019). Attributing mortality from temperature extremes: A time series analysis in Varanasi, India. *Science of the Total Environment*, 665, 453-464.

Singh, S., Mall, R. K., Dadich, J., Verma, S., Singh, J. V., & Gupta, A. (2021). Evaluation of CORDEX- South Asia regional climate models for heat wave simulations over India. *Atmospheric Research*, 248, 105228. https://doi.org/10.1016/j.atmosres.2020.105228

Singh, S., Mall, R. K., & Singh, N. (2021). Changing spatio-temporal trends of heat wave and severe heat wave events over India: An emerging health hazard. *International Journal of Climatology*, 41(S1), E1831–E1845. https://doi.org/10.1002/joc.6814

Singh, N., Mall, R. K., Banerjee, T., & Gupta, A. (2021). Association between climate and infectious diseases among children in Varanasi city, India: A prospective cohort study. *Science of The Total Environment*, 796, 148769.

Singh, C., Madhavan, M., Arvind, J. and Bazaz, A., 2021. Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate*, *36*, p.100783.

Sridhar, K.S., 2016. Economic Impacts of Climate Change in India's Cities. In *Climate change challenge (3C) and social-economic-ecological interface-building* (pp. 279-295). Springer, Cham.

Srinivasan, J., 2019. Impact of climate change on India. In *India in a Warming World* (pp. 31-44). Oxford University Press.

Taenzler, D., Ruettinger, L., Ziegenhagen, K., Murthy, G., 2011. Academy of Gandhian Studies Water, Crisis and climate change Climate Change in India: A Policy Brief, Retrieved form: 2011_water_crisis_and_climate_change_in_india_a_policy_brief.pdf (adelphi.de).(assessed March 27, 2023).

UN SDGs (2022). United Nations: The Sustainable Development Goals Report 2022. Available at https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf.

UN DESA (2018). https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (access on 09 Nov 2022)

UN DESA, 2014. World Urbanization Prospects: The 2014 Revision, Highlights. New York: Population Division, United Nations Division of Economic and Social Affairs (UN DESA).

UN DESA, 2021. UNDESA World Social Report 2021. Department of Economic and Social Affairs, United Nations Division of Economic and Social Affairs (UN DESA). https://www.un.org/development/desa/dspd/world-social-report/2021-2.html

United Nations, The Sustainable Development Goals Report 2022. Department of Economic and Social Affairs (DESA), New York, USA. https://unstats.un.org/sdgs/report/2022/

Unnikrishnan, A.S. and Shankar, D., 2007. Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates?. *Global and Planetary Change*, *57*(3-4), pp.301-307.

Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A. and Cox, P.M., 2015. Health and climate change: policy responses to protect public health. *The lancet*, *386*(10006), pp.1861-1914.

West Bengal Pollution Control Board, 2005. Air Quality Management: Final Report. New Delhi: WBPCB in Collaboration with Asian Development Bank; Intercontinental Consultant and Technocrats Pvt. Ltd.

WHO, 2016. WHO Global Urban Ambient Air Pollution Database (update 2016). World Heath Organization (WHO), Geneva, Switzerland.

World Health Organization, WHO (2022). https://www.who.int/news/item/07-10-2022-building-climate-resilient-health-services-with-sustainable-energy

Yenneti, K., Tripathi, S., Wei, Y.D., Chen, W. and Joshi, G., 2016. The truly disadvantaged? Assessing social vulnerability to climate change in urban India. *Habitat International*, *56*, pp.124-135.

CHAPTER 7: HYDROLOGY AND CRYOSPHERE

Vimal Mishra

Coordinating Lead Author
Prof. Vimal Mishra, IIT Gandhinagar

Lead Author
Swarup Dangar, PhD student, IIT Gandhinagar

BACKGROUND

The water cycle is modified by both climatic and anthropogenic factors (Douville et al., 2021). The earth's energy budget changes are driven by anthropogenic forcings (greenhouse gases, aerosols, surface albedo) [Douville et al., 2021]. A warming climate will hold more moisture content, increases moisture transport into weather systems, and intensifies wetter events (Giorgi et al., 2019; Allan et al., 2020). Aerosol variations affect precipitation patterns associated with the monsoonal climate (Ganguly et al., 2012; Singh et al., 2019). Warming climate can also lead to increases in snowfall intensity locally (Allan et al., 2020) and changing the river flows seasonality. An increase in CO_2 concentrations generally decreases plant transpiration, which affects soil moisture, streamflow, moisture recycling, and surface temperature (Skinner et al., 2017). However, increased leaf area might offset these changes (Zhu Z. et al., 2016; Zeng Z. et al., 2018). Human interventions like groundwater abstraction, dams and reservoirs, urbanization, and inter-basin transfers have their own consequences. Irrigation changes groundwater levels, local precipitation (Alter et al., 2015; Cook et al., 2015, de Vrese et al., 2016), and monsoon timing (Guimberteau et al., 2012). Land cover changes and urbanization affect precipitation, evapotranspiration (Li et al., 2015; Douville et al., 2021, Wang et al., 2018), infiltration (Sun et al., 2018), runoff (Bosmans et al., 2017), surface permeability (Choi et al., 2016), and sensible heat flux (Kusaka et al., 2014, Niyogi et al., 2017).

Changes in Precipitation

The Indian summer monsoon rainfall (ISMR) has considerable spatial heterogeneity. The high rainfall zones are concentrated in east-central India, while northwest and rain shadow southern India receives low rainfall. The annual average rainfall does not show any trend for the 1901-2015 period, while the recent 1951-2020 period shows a non-significant declining trend (Mishra et al., 2012). Most of the declining trend in the observed summer monsoon rainfall is centered over the Indo-Gangetic Plain, the northeast region, and the Western Ghats. Northward ITCZ shifts with the northern hemisphere warming, which is associated with rainfall deficits in India (Bonfils et al., 2020). The other contributing factors to rainfall changes include anthropogenic aerosols, equatorial Indian Ocean warming, and urbanization with agricultural intensification (Paul et al., 2018, Krishnan et al., 2016; Mishra et al., 2012; Roxy et al., 2015). In the recent period (1976-2015), central and extreme northeastern parts and Kerala have undergone a decrease in rainfall while there is an increase in the parts of western India

(Kulkarni et al. 2017). However, the faster rate of land surface warming than the ocean has favored monsoon revival in recent decades (2002-2014) [Jin and Wang 2017].

The northeast monsoon rainfall from October to December is a major source of annual rainfall (40%) in South India (Rajeevan et al., 2012, Mishra et al., 2021), exhibiting intraseasonal variability of 20-40 days. When the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are in their positive phases, they tend to create conditions that are favorable for normal to above-normal rainfall during the Northeast Monsoon season (Rajeevan et al., 2012). Apart from the changes in the summer monsoon season mean rainfall, climate change impacted the northeast monsoon from 1959-2016 as high-intensity rainfall events increased (Nageswararao et al. 2019). In this period, a statistically significant increase in dry spell frequency, wet spell intensity, and a decrease in dry spell intensity has been found (Singh et al., 2014). The summer monsoon onset varies with El Nino Southern Oscillation (ENSO), with early and late onset preceded by La Nina and El Nino, respectively (Noska and Mishra 2016). A significant increasing trend is observed in the frequency and intensity of extreme rainfall along with decreasing trend in moderate rainfall (Goswami et al., 2006, Krishnan et al., 2016; Roxy et al., 2017; Asoka et al., 2018). Low-intensity rainy days have declined while extreme precipitation events have increased in India (Asoka et al., 2018). The heavy precipitation events intensity has increased in most regions of India (IPCC). Most tropical cyclones in the North Indian Ocean come from the Bay of Bengal and a few from the Arabian Sea. Over the past 40 years (1981-2021), the number of tropical cyclones hasn't changed much, but there has been a three-fold increase with compound extremes in the last 10 years (2011-2021) (Rajeev and Mishra, 2023).

Paleoclimate proxies also indicate long-term changes in the precipitation variability over India. The Himalayan region has shown a declining trend in the last 200 years from tree rings datasets with greenhouse warming and anthropogenic aerosol emissions (Xu et al. 2013, Shi et al. 2017). The northeast, central, and peninsular India has larger multidecadal monsoonal variations in the Holocene than in the present (Sinha 2018). Declining summer monsoon in the Holocene epoch with multidecadal to centennial-scale variability (Chao and Chen 2001) was linked to Intertropical convergence zone (ITCZ) southward migration (Fleitmann et al. 2007).

Anthropogenic emissions are likely the primary driver of global-scale heavy precipitation intensification in land areas. Most climate models project an increase in the summer monsoon precipitation as moisture supply increases with global warming (Krishnan et al., 2013, Mei et al., 2015). However, climate models also indicate a weakening of large-scale monsoonal circulation (Krishnan et al. 2016). The weak convective coupling in the global climate models results in poor skill in the monsoon simulations (Krishnan et al. 2016). The projected mean precipitation changes at 1.5C warming range from a 10-20% decrease to a 40-50% increase, making the multi-model median near zero (IPCC).

The intermodal spread and uncertainty in the projected changes in rainfall make hydroclimatic assessment uncertain (Saha et al. 2014). A significant increase in interannual variation during the summer monsoon is projected from CMIP5 models (Menon et al. 2013). Maximum 1-5 day precipitation of 5-500 year return period is projected to increase by 10-30% under the RCP8.5 scenario (Mukherjee et al. 2018). The extreme precipitation frequency in southern and central India is also projected to rise in the mid and end periods of the 21st century (Mukherjee et al. 2018). Some parts of India are projected to experience precipitation changes of 70% from the historical mean under 4C global warming (IPCC). Uncertainties in precipitation changes from internal variability persist and are comparable to model uncertainties by the end of 2100 (Singh and AchutaRao 2018). Moreover, uncertainty in the northwest's arid region is higher than in west-central India (Singh and AchutaRao, 2018). The Indian monsoon intensification in a warming climate is in consensus despite the model uncertainties in rainfall extremes changes (Singh et al., 2019). Precipitation projections cannot provide precise confidence, and risk assessments should be done considering the uncertainty bounds (IPCC).

Changes in Evapotranspiration and Soil Moisture

Evapotranspiration (ET) is governed by increasing atmospheric water demand and greening and partly by anthropogenic forcing (IPCC). ET on a regional scale depends on the climate, land cover, and irrigation. A warming climate increases evaporation (Berg et al., 2016), while rainfall affects soil moisture available for evaporation (Hovenden et al., 2014). Vegetation changes also play a role in the land-atmosphere fluxes as transpiration losses (Good et al., 2015). Irrigation results in an evapotranspiration increase in Indian subcontinental river basins, with an increase of 47% in the Indus and 12% in the Ganga basins (Shah et al., 2018). However, a potential evapotranspiration decline was observed in India from 1971-2010 (Padmakumari et al., 2013, Aadhar and Mishra, 2020). A larger increase in ET is observed in southern India (IPCC).

Irrigation, precipitation, and ET affect soil moisture and aridity changes. A significant decline in dry season soil moisture (~4%) occurred during the 1951-2018 period (Mishra 2020). The main contributor is the decline in the late summer monsoon rainfall (30%) and dry season rainfall (34%), while the dry season warming contribution (15%) is less (Mishra 2020). Soil moisture in the dry season (October-December) showed a declining trend between 1982-2018 in central India and Indo-Gangetic plain (Dangar et al., 2021). However, the Normalized Difference Vegetation Index (NDVI) showed an increase primarily due to irrigation mostly from groundwater for food production (Dangar et al., 2021). Tree-ring stable isotopes in the Himalayas suggest intensifying forest evapotranspiration due to the combination of warmer temperatures and increased CO_2 levels, leading to increased extreme rainfall events in recent decades (Singh et al., 2021).

Irrigation reduces the land surface temperature while increasing evapotranspiration (Ambika and Mishra 2019, Li and Xiao 2019) and latent heat flux (Seneviratne et al. 2010). The aridity increases due to land atmospheric demand rising, surpassing the precipitation changes (Berg et al. 2016). Irrigation impacts the land-atmosphere coupling (Seneviratne et al. 2010), and feedback between soil moisture, air temperature, and precipitation leads to weather changes. Soil moisture deficit acts as a limiting factor for net primary productivity and ecosystem carbon uptake (Green et al. 2019). Land-atmosphere feedback further amplifies the soil moisture feedback (Zhou et al. 2019). Irrigation in the Indo-Gangetic Plain (IGP) resulted in cooling, soil moisture increase, and atmospheric aridity reduction between 1979-2018 (Ambika and Mishra 2020). Therefore, the modulation by irrigation can reduce the combined risk of low soil moisture and high vapor pressure deficit during droughts (Thiery et al., 2020, Zhou et al., 2019).

The CESM-LENS simulations indicate summer monsoon rainfall projections of 6% by 2100 with a 4°C rise in temperature, resulting in a 10% increase in potential evapotranspiration (Mishra et al., 2020). CMIP5 and CMIP6 models project an increase in PET and drought frequency over most regions in India (Aadhar and Mishra, 2020, Aadhar and Mishra, 2020). The carbon dioxide emissions on plant physiology and leaf area increase will play a role in ET projected changes, but the overall contribution to ET changes is low confidence (IPCC). Surface soil moisture is projected to decline in a warming climate, and this combined effect will result in an increase in the frequency of concurrent hot and dry monsoon extremes (Mishra et al., 2020). The relative contribution of physiological effects of CO_2 and climate on future ET and soil moisture remains a knowledge gap with uncertainties in climate sensitivity in CMIP6 models (IPCC).

Changes in Cryosphere

The Hindu Kush Himalaya (HKH) has a tropical/subtropical climate from mountain foothills to higher altitudes with permanent ice and snow-covered peaks (Pant et al. 2018). Higher elevations above 4500m experience far below freezing temperatures and receive snow. The mountainous regions have a faster temperature increase rate than global warming (Pepin et al., 2015). The total glacial areas have shrunk in the Himalayas at an annual rate of -0.36% per year during 1960-2010 (Azam et al., 2018). Himalayan mass loss from glaciers has been accelerating over the past 40 years (1975-2016) [Maurer et al., 2019]. Himalayan glaciers have lost mass at a rate of 0.37±0.15 m per year between 2000 to 2016 (Brun et al., 2017) and 0.4±0.1 m per year between 2000-2018 (Shean et al., 2020). The Karakoram glacier shrinking is not significant, with a mean mass loss rate of 0.03±0.07 m per year during 2000-2016 (Brun et al., 2017). The mass lost from Himalayan glaciers is accelerating, while Karakoram glaciers have relatively stable (Azam et al., 2018). The cause of accelerating mass loss in the Himalayas is rising temperatures and precipitation decline at high altitudes (Nie et al., 2017), while Karakoram glaciers are relatively stable due to a balance between accumulation and ablation changes (Bolch et al., 2012). The Karakoram Himalayas seem to have gained slight glacial mass in the early 21st century (Gardelle et al., 2012, Kapnick et al., 2014).

The Hindu Kush Himalayas are warming faster than the mean global warming (Sreshtha et al., 2015). The aerosols (black carbon) at higher elevations can enhance the warming and melting rate (Ramanathan and Carmichael, 2008). Projected increases in temperature and precipitation will lead to more glacier mass loss, although with variability in climate models and scenarios (Kraaijenbrink et al., 2017, Lutz et al., 2014). Even under 1.5°C global warming levels, High Mountain Asia will have projected warming of 2.1±0.1 °C, resulting in a mass loss of 36+7% (RCP2.6) and 49+7% (RCP4.5) by 2100 (Kraaijenbrink et al., 2017). Seasonal meltwater plays a significant role in the Indus basin, while in Brahmaputra and Ganges basins, the role is secondary due to the coincidence of melt season with precipitation (Lutz et al., 2014). Runoff peak delays from glacial melt under RCP8.5 as more warming will generate more melt rate to compensate for shrinking glaciers area, delaying runoff (Huss et al., 2018). Seasonal runoff from glaciers is predicted to rise in June and decline in July-September by 2100 (Huss et al., 2018). Projected changes in runoff will impact hydropower production in high mountain regions (Ali et al., 2018). The lack of observational data is the knowledge gap for evaluating models for cryosphere simulations (IPCC).

Glacial meltwater runoff is likely to peak in the next decades under climate change, and after that, the runoff will decline due to the shrinking of glacial mass (Huss et al., 2018). However, uncertainties exist in the timing and magnitude of the peak and subsequent decline. Therefore, basin runoff will be more rain-dominated (Immerzeel et al., 2012) with decreasing modulating effect of glaciers, enhancing the impact of droughts and floods (Pritchard et al., 2019). Glacial lake outbursts and flood frequency have increased, posing a threat to downstream hydropower infrastructure (Schwanghart et al., 2016).

Reducing global warming will diminish the glacial mass loss and give enough time for climate adaptation pathways (Nie et al., 2021).

Changes in Streamflow and floods

The mean annual total simulated runoff ranges between 100-1500 mm from the semi-arid western parts (Sabarmati basin) to the eastern regions (Brahmaputra basin), mainly due to precipitation variability (Shah and Mishra, 2018). The eastern basins i.e. Brahmaputra, Mahanadi, Cauvery, Brahmani, and Subarnekha show an increasing trend in runoff during 1970-1999 (Shah and Mishra, 2016). The declining trend in runoff is observed in Ganga, Indus, Krishna, Westcoast, Mahi, Sabarmati, and Tapi basins (Shah and Mishra, 2016). Streamflow projections show an increase of 20% in central and peninsular gauge locations while declining streamflow for Ganga, Indus, and coastal gauge stations for the RCP2.6 scenario (Shah and Mishra, 2018). Most gauge stations in India show a projected increase in streamflow for the RCP8.5 scenario during the near (10%), mid (20%), and far (25%) periods (Shah and Mishra, 2018). The ensemble of hydrological and climate models also shows surface runoff increases over most of India, spanning the Deccan plateau (Schewe et al., 2014).

Climate change and human interventions control the magnitude and signs of runoff and streamflow changes. The human influence on the streamflow is consistent with a decrease in mean flows in India (IPCC). Human activities such as irrigation water withdrawal, land use changes, and reservoir regulation can significantly reduce runoff (Zaherpour et al., 2018). Water yield is highest for the Indus (~732+50 km^3), Ganga (~582+89 km^3), and Brahmaputra basins (~231+71 km^3) based on multimodel estimates for the 1951-2016 period (Kushwaha et al., 2021). Of the 18 Indian subcontinental basins, two (Brahmaputra and West Coast) are energy limited as per the Budyko framework, meaning the rest basins have higher atmospheric water demands (Kushwaha et al., 2021). The streamflow drought extent aligns with the increase in drought extent from meteorological drought (Sharma and Mujumdar 2017). Hydropower production in India is projected to rise to 25% by 2100 with increased precipitation under the RCP8.5 scenario (IPCC).

Floods occur at shorter timescales of days and mainly during India's southwest monsoon season. Foods in south peninsular India occurs during the southwest monsoon (Dhar and Nandargi, 2003). Central India experiences floods during the active phase of the monsoon, whereas the Himalayan foothills experience floods during the break phase (Dhar and Nandargi, 2003). Flood frequency increased fourfold in the tropics after 2000 (Najibi and Devineni, 2018). Severe flood events frequency indicates a significant trend of one flood event per decade in India from 1985 to 2019 using the Dartmouth flood observatory database (Krishnan et al., 2020). The major urban recent flood events in India occurred in 2005 (Mumbai, Bangalore, Chennai), 2007 (Bangalore, Chennai, Kolkata), 2014 (Mumbai), 2015 (Bangalore, Chennai), and 2017 (Mumbai, Ahmadabad, Kolkata) (Krishnan et al., 2020). The major recent river floods were recorded in Bihar (2007, 2008, 2017), North-east India (Brahmaputra basin) (2012, 2013, 2015, 2016, 2017), Uttarakhand (2013), and Kerala (2018) (Krishnan et al., 2020, Mishra and Shah, 2018, Vellore et al., 2016).

Floods lead to crop and harvest failure, reducing crop yields. Heavy rainfall events, multi-day precipitation, and antecedent soil moisture conditions are linked to flood occurrences (Garg and Mishra, WRR; Sharma et al., 2018, Nanditha and Mishra, 2022). Other factors include urbanization, dams, reservoirs, snowmelt, basin catchment characteristics, and infrastructure that can accelerate the flood impacts (Rosenzweig et al., 2010, Mishra and Lilhare, 2016). The floods are linked to large-scale climatic teleconnections like ENSO, NAO, AMO, and PDO (Ward et al. 2016; Najibi and Devineni 2018). Flood duration is sensitive to ENSO conditions, and occurrences of long-duration floods are associated with El Nino and La Nina years (Ward et al. 2016). The extreme floods in the Brahmaputra basin during 2012, 2016, and 2017 occurred during the La Nina years (Pervez and Henebry, 2015). Analysis from observations and global climate models show that the 2015 Chennai floods could not be attributed to anthropogenic climate change as the impacts of greenhouse gas emissions being counteracted by aerosols (van Oldenborgh et al., 2017). The increasing flood events in the Ganga-Brahmaputra basins, along with land subsidence and glacial and snowmelt into rivers, make it a compound event (Lutz et al., 2014).

Flood extremes are rising post-1950s (Ali et al., 2019) with an increase in extreme rainfall events (Goswami et al., 2006; Rajeevan et al., 2008), intensification of cyclones (Kishtawal et al., 2012), and long-term climate variability (Ward et al., 2016; Najibi and Devineni 2018). The projected rise in short-duration rainfall extremes leads to flood risk in urban parts of India (Ali and Mishra, 2018). The 3-hourly 100-year return period precipitation maxima are projected to increase by 30% under the nonstationary conditions in 1.5C warming (Ali and Mishra, 2018). The Indus-Ganga-Brahmaputra (IGB) basin is a projected flood-risk zone (Wijngaard et al., 2017; Lutz et al., 2019). Ganges, Brahmaputra, and southern peninsular India are projected to have a higher frequency of floods in the twenty-first century (Hirabayashi et al., 2013). Multi-day precipitation is the primary driver of high flows in both observed and projected climates (Nanditha and Mishra, 2022). The high-flow events frequency is projected to increase by 50-75% by 2100, depending on SSP scenarios (Nanditha and Mishra, 2022). A significant projected increase in compound extreme events of extreme precipitation on wet antecedent soil moisture has implications for future floods (Nanditha and Mishra, 2022). Assessing flood events and the relationship of flood peaks with extreme precipitation, temperature, and soil moisture conditions to understand the drivers of flood mechanisms will help in flood forecasting (Blöschl et al., 2019; Wasko et al., 2020).

Early warning systems for flood forecasting, prediction, and hazard monitoring to take timely action in advance can reduce the risk of flood casualties and infrastructure. However, flood risk cannot be eliminated completely with any flood adaptation measure. Flood adaptation should be considered at the local and community levels considering the flood types and livelihoods (Fenton et al., 2017). Flood management saves human lives but for reducing infrastructure damage and livelihood sustainability, it is ineffective (Ferdous et al., 2019). Flood hazards and vulnerability studies must consider the interplay of water and society and community adaptive capacity, particularly in projected flood risk vulnerable groups (IPCC).

Changes in Droughts

Extended dry spells affect water availability, especially in arid parts of India. Drought types are interconnected with the propagation of one to another over time. Meteorological droughts (low precipitation spells) lead to soil moisture deficits and streamflow reduction i.e. hydrological drought. Plants get water stressed due to increased evaporative demand leading to agricultural or ecological drought. Long-term droughts impact hydrological components like streamflow, groundwater, and total water availability, as experienced in the Indo-Gangetic plain in 2015 (Mishra and Singh, 2010, Mishra et al., 2016). Hydrological drought results in a water supply reduction, agricultural drought impacts food production, ecological drought increases wildfire risk, and cascading droughts can cause human migration (IPCC). Terrestrial water storage drought combines hydrological, agricultural, and ecological drought.

All India drought was declared by the India meteorological department (IMD) in 2002 as 30% of India is affected by >25% precipitation deficit in monsoon (Mishra, 2020). The drought caused a reduction in food production of rice (22%), oilseeds (23.5%), and wheat (9.5%) (Shah et al., 2009). Increases have been noted in the summer monsoon droughts frequency, duration, and intensity post-1960 compared to pre-1960 (Mallya et al. 2016; Mishra et al. 2016). A significant drying trend was observed in humid central regions and northern India using rainfall observations (Krishnan et al. 2013) and drought indices (Pai et al. 2011), along with an increase in aridity (Yang et al. 2019). Frequent and high-intensity droughts threaten food and water security by depleting soil moisture and groundwater (Asoka et al. 2017). The frequency and areal extent of soil moisture droughts increased between 1980-2008, hampering crop production in India (Mishra et al. 2014). Drought increase is possibly attributed to anthropogenic influence on weakening monsoon circulation and rainfall (Krishnan et al. 2016). Southwest monsoon droughts are generally related to sea surface temperature (SST) variations, especially the warm phase of El Niño–Southern Oscillation (ENSO) and negative Indian Ocean Dipole (IOD) events (Pai et al. 2017; Mishra et al. 2012). Northeast monsoon droughts are linked with the negative phase of ENSO (La Nina) and IOD (Kripalani and Kumar 2004; Mishra et al., 2021).

India experienced ten major droughts between 1950-1989, while five major droughts post 2000 (Pai et al., 2017), with the 2015 drought as the most severe, causing crop damage (Mishra et al., 2016). The worst monsoon season drought occurred in 2002 with ~54% areal extent compared to 2009 (~45%) and 2014 (~35%), leading to considerably low crop yields (Mishra et al., 2021). Flash droughts mostly occur during the summer monsoon in India, with major occurrences in 1979, 2001, 1958, and 1986 (Mahto and Mishra, 2020). Non-monsoon flash droughts occur in the peninsular and Himalayan regions due to northeast monsoon and western disturbances (Mahto and Mishra, 2020). The northeast monsoon deficit of more than 40% during the 2016-2018 period is the driest in 150 years, causing unprecedented drought and water scarcity in South India and are associated with the equatorial Indian and Pacific Ocean cool phase (Mishra et al., 2021).

An increase in drought intensity towards the end of the twenty-first century is probable (Krishnan et al. 2016). The areal extent of severe drought is projected to increase (150%) with warming under the RCP8.5 scenario (Aadhar and Mishra 2018). In a warming climate, atmospheric water demand rises, leading to soil moisture depletion and prolonged droughts. The frequency of meteorological, hydrological, and agricultural droughts is projected to increase with the warming climate (Aadhar and Mishra, 2020). In eastern India, a projected decrease in extreme droughts is likely (IPCC). The concurrent hot and dry extremes frequency will increase by 1.5 times under warming in the 21st century (Mishra et al., 2020). The population exposure is likely to rise threefold to dry and wet extremes under a 2°C warming climate (Kumar and Mishra, 2021). The combined areal extent of dry and wet extremes affected regions is expected to increase by 25-30% in most (80%) of India under a 1.5°C or 2°C warming world (Kumar and Mishra, 2021).

Drought indicators related to soil moisture and water availability will lead to more societal impact and is a vital knowledge gap (IPCC). The choice of drought indicators also affects the magnitude and signs of drought change in a warming climate. Uncertainties in drought projections arise due to uncertainties in regional climate, population projections in different scenarios, and plant physiological responses to warming (IPCC).

Changes in Groundwater

India has an extensive area under groundwater irrigation (Siebert et al., 2010), contributing to food production for 24% global population with 30% of global irrigated land (Dangar et al., 2021). Irrigation is vital in alleviating poverty and reducing vulnerability and risks (Balasubramanya and Stifel, 2020). Irrigation-based groundwater depletion has increased globally from 2000 to 2010, of which 23% is contributed by India (Dalin et al., 2017). Groundwater acts as a buffer during droughts when soil moisture depletes. However, extensive abstraction during dry periods can worsen groundwater levels and drought conditions (Van Loon et al., 2016). India is among the top contributors to the international food trade, where 11% of irrigation water comes from non-renewable sources (Dalin et al., 2017). India mainly uses the crops from groundwater irrigation for domestic consumption, and ~4% is exported to other countries (Dalin et al., 2017). India is still the world's third-largest groundwater-based exporter, with the majority being rice (25%) and cotton (24%) exported to China (Dalin et al., 2017). Blue water scarcity during crop growing is met with unsustainable abstraction to complete the irrigation water requirements (Rosa et al., 2020). Over-extraction of groundwater leads to streamflow declines in the human-dominated watersheds and in the downstream regions (Condon and Maxwell, 2019, Penny et al., 2020), as baseflow to the Ganga River reduces during summer (Mukherjee et al., 2018). The upper Ganges and Indus basins are groundwater hotspots (Gleeson et al., 2012) and have already reached environmental flow limits (de Graaf et al., 2019).

Groundwater depletion has spatial heterogeneity, with northern India showing a significant decline of 15-25 cm per year, while in southern India, an increase of 1-2 cm per year during the 2002-2013 period from GRACE measurements (Asoka et al., 2017). Groundwater is abstracted during post and pre-monsoons for rice and wheat irrigation in the north and central India (Asoka et al., 2017; Rodell et al., 2018). Rodell et al. (2018) estimated a depletion rate of 19.2+1.1 Gt/yr in north India and an increasing trend of 9.4+0.6 Gt/yr in central and south India during 2002-2016. Punjab is the hotspot with the highest non-renewable groundwater withdrawal of 34.7 km3 (Panda and Wahr, 2016), with 20.4 km3 of renewable groundwater (CGWB, 2014). Northwest India has a high groundwater pumping rate (Rodell et al., 2009, Tiwari et al., 2009) with more than 20m deep water table (MacDonald et al., 2016). Subsidized electricity with water-intensive crop farming leads to a rapid decline of groundwater in India (Mishra et al., 2018).

Groundwater and monsoon season rainfall are connected (Asoka et al., 2017, Rodell et al., 2018). Groundwater well recharge median trends from 1996-2013 are positive or negative, with increasing or declining precipitation (Asoka et al., 2018). In north India, monsoon season groundwater recharge is favoured by low-intensity rainfall, while in south India, high-intensity rainfall is beneficial (Asoka et al., 2018). The Ganga River basin lost around ~227±25 km^3 of groundwater between 2002-2016, about 20 times the largest reservoir Indira Sagar (Dangar and Mishra, 2021). Significant summer monsoon decline (~11%) during 1951-2016 and frequent droughts of 2009 and 2014-2015 in the Ganga basin have depleted the groundwater; however, the major contributor (80%) is from nonrenewable groundwater abstraction (Dangar and Mishra, 2021). Extreme rainfall increase in central India is associated with intensified paddy cultivation in northwest India (Devanand et al., 2019). Therefore, irrigation in India is also sensitive to rainfall pattern modification (Mathur and AchutaRao, 2020).

A considerable increase in green and blue water consumption for wheat and maize crops and a slight lowering in blue water consumption for paddy is projected (Mali et al., 2021). An increase in future groundwater storage in semiarid northwest India is projected, associated with increased precipitation projections without considering local hydrogeological characteristics (Wu et al., 2020). Irrigation expansion will offset the positive recharge of groundwater (Wu et al., 2020) with increased unsustainable groundwater pumping (Zaveri et al., 2016). Groundwater withdrawal is projected to continue to deplete in the long term due to non-renewable abstractions and can nullify the increase in groundwater recharge (Dangar and Mishra 202X, IPCC). So, the sustainability of groundwater resources cannot be ensured until non-renewable extraction is limited. The sensitivity of recharge processes to climate variability and pumping with hydrological models and GRACE satellite-based estimates provides important insights at regional scales (Rodell et al., 2018); however, it fails to capture more localized depletion or recharge. The gaps and unavailability of long-term readily available groundwater level monitoring data make it challenging to understand groundwater storage at a regional scale and test the performance of high-resolution modeling (Gleeson et al., 2020). The limitations of monitoring networks with abstraction data and groundwater process representation with climate feedback constrain our understanding of groundwater variations (IPCC).

Major questions related to climate change impacts on water sector:

- How will the interplay between climate and anthropogenic drivers (aerosols, LULC, irrigation) affect the summer and northeast monsoon changes and variability?
- How will rainfall characteristics (mean, intensity, and duration) change in the future, and what will be its implications on surface and groundwater storage?
- How will changes in the future irrigation-related water withdrawal impact overall water sustainability?
- How will summer season variability in streamflow changes in the Himalayan River basins in a warming climate?
- How do hydrological extremes (drought and floods) and compound extremes change, affecting water availability in the future?
- How will human interventions (reservoir operations, groundwater abstraction) affect the hydrological cycle under climate change?
- What are the impacts of urbanization on water sustainability under climate change, and how does it act as a pressure factor?
- How coastal water tables, infrastructure, and ecosystems are impacted by flooding?
- How to devise more reliable and regional scale high-resolution projections for the water sector adaptation?
- How atmospheric rivers be a component of the current flood early warning systems to assist in both adaptation and mitigation efforts?

Priority areas for short and long terms:

Precipitation

- Convective parameterization in models
- Identification of coupled interactions (air-sea, land-atmosphere, flow-orography)
- High-quality observation (atmosphere and ocean)
- Biogeophysical process-based land surface models
- ENSO-monsoon relationship in models
- Countrywide surface GHGs concentration observation network and fluxes at urban and ecological hotspots
- Aerosol observational data

Cryosphere

- Long-term records and field measurements of weather, ice thickness, or debris depth in the Himalayan cryosphere
- Glacial-lake-weather interactions studies and representations of the regional cryospheric process in climate models
- Wide array of open-data weather stations, river-flow gauges, and glacier mass balance monitoring sites is needed
- Monitoring high-altitude rainfall and snowfall along with ice and debris thickness surveys to enhance process-based understanding of glacier evolution and regional hydrological impacts under climate change.
- Sensors will contribute to the transboundary hazard-warning system and water–energy–food security

Groundwater

- An optimal groundwater monitoring network needs to be set up with an increased sampling frequency once a month.
- Evaluation of land surface models against in-situ observations of soil moisture, evapotranspiration, groundwater level, and streamflow in India.
- New approaches to downscale observations at various spatial and temporal resolutions e.g. machine learning and process-based modeling.
- Appropriate policies for groundwater utilization, seawater intrusion, and human-induced subsidence in coastal cities.

Floods

- Assessing uncertainties in observations, correcting satellite observations, and improving forecasts via data assimilation.
- Lack of dense observational networks for variables like soil moisture, streamflow, groundwater wells, water, and energy fluxes.
- Incorporating additional low-cost and robust sensors to improve hydrological model consistency and predictive ability.

- Dynamic operational curves for reservoir operations with focus on flood mitigation.
- Ensemble flood prediction system from the existing ensemble precipitation forecast at multi scales for flood-prone catchments and urban areas.
- Flood preparedness at the community level.
- Dynamic simulations of flood inundation, impact modeling, and cost-benefit analysis to reduce coastal flood exposure due to relative sea-level rise.

Droughts

- Data collection for better lead identification and declaration of drought based on understanding drought characteristics.
- Framework to capture drought mechanism and propagation using coupled human-water interactions.
- Constraining the uncertainties in hydrological and climate models and using reasonable drought indices for planning and water resources management.
- Impact of urbanization and agriculture in hydroclimatic extremes at multiscale.
- Attribution-based studies of anthropogenic climate change for droughts and floods variability.

REFERENCES

Aadhar, S. and Mishra, V. (2018). Impact of climate change on drought frequency over India. Book Climate Change and Water Resources in India Publisher: Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India.

Aadhar, S. and Mishra, V. (2020a). Increased drought risk in South Asia under warming climate: Implications of uncertainty in potential evapotranspiration estimates. Journal of Hydrometeorology.

Aadhar, S. and Mishra, V. (2020b). On the Projected Decline in Droughts Over South Asia in CMIP6 Multimodel Ensemble. Journal of Geophysical Research: Atmospheres, 125(20):e2020JD033587.

Ali, H. and Mishra, V. (2018). Increase in Subdaily Precipitation Extremes in India Under 1.5 and 2.0 °C Warming Worlds. Geophysical Research Letters, 45(14):6972–6982.

Ali, H., Modi, P., and Mishra, V. (2019). Increased flood risk in Indian sub-continent under the warming climate. Weather and Climate Extremes, 25:100212.

Ali, S. A., Aadhar, S., Shah, H. L., and Mishra, V. (2018). Projected Increase in Hydropower Production in India under Climate Change. Scientific Reports 2018 8:1, 8(1):1–12.

Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., Gan, T. Y., Pendergrass, A. G., Rosenfeld, D., Swann,A. L., Wilcox, L. J., and Zolina, O. (2020). Advances in understanding large-scale responses of the water cycle to climate change. Annals of the New York Academy of Sciences, 1472(1):49–75.

Ambika, A. K. and Mishra, V. (2019). Observational Evidence of Irrigation Influence on Vegetation Health and Land Surface Temperature in India. Geophysical Research Letters, 46(22):13441–13451.

Ambika, A. K. and Mishra, V. (2020). Substantial decline in atmospheric aridity due to irrigation in India. Environmental Research Letters, 15(12):124060.

Asoka, A., Gleeson, T., Wada, Y., and Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nature Geoscience, 10(2):109–117.

Asoka, A., Wada, Y., Fishman, R., and Mishra, V. (2018). Strong Linkage Between Precipitation Intensity and Monsoon Season Groundwater Recharge in India. Geophysical Research Letters, 45(11):5536–5544.

Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., and Kargel, J. S. (2018). Review of the status and mass changes of Himalayan-Karakoram glaciers. Journal of Glaciology, 64(243):61–74.

Balasubramanya, S. and Stifel, D. (2020). Water, agriculture & poverty in an era of climate change: Why do we know so little? Food Policy, 93:101905.

Berg, A., Findell, K., Lintner, B., Giannini, A., Seneviratne, S. I., Van Den Hurk, B., Lorenz, R., Pitman, A., Hagemann, S., Meier, A., Cheruy, F., Ducharne, A., Malyshev, S., and Milly, P. C. (2016). Land–atmosphere feedbacks amplify aridity increase over land under global warming. Nature Climate Change 2016 6:9, 6(9):869–874.

Bl¨oschl, G., Hall, J., Viglione, A., Perdig˜ao, R. A., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Boh´aˇc, M., Bonacci, O., Borga, M., ˇCanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., G¨ul, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnov´a, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J. L., Sauquet, E., ˇSraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., and ˇZivkovi´c, N. (2019). Changing climate both increases and decreases European river floods. Nature 2019 573:7772, 573(7772):108–111.

Bolch, T., Kulkarni, A., K¨a¨ab, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M. (2012). The state and fate of himalayan glaciers. Science, 336(6079):310–314.

Bonfils, C. J. W., Santer, B. D., Fyfe, J. C., Marvel, K., Phillips, T. J., and Zimmerman, S. R. H. (2020). Human influence on joint changes in temperature, rainfall and continental aridity. Nature Climate Change, 10(8):726–731.

Bosmans, J. H., Van Beek, L. P., Sutanudjaja, E. H., and Bierkens, M. F. (2017). Hydrological impacts of global land cover change and human water use. Hydrology and Earth System Sciences, 21(11):5603–5626.

Brun, F., Berthier, E., Wagnon, P., K¨a¨ab, A., and Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. Nature Geoscience 2017 10:9, 10(9):668–673.

CGWB (2014). Ministry of Water Resources GOVT OF INDIA Faridabad GROUND WATER YEAR BOOK-INDIA 2013-14.

Chao, W. C. and Chen, B. (2001). The Origin of Monsoons. Journal of the Atmospheric Sciences, 58(22):3497–3507.

Condon, L. E. and Maxwell, R. M. (2019). Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. Science Advances, 5(6):eaav4574.

Cook, B. I., Shukla, S. P., Puma, M. J., and Nazarenko, L. S. (2015). Irrigation as an historical climate forcing. Climate Dynamics, 44(5-6):1715–1730.

Dalin, C., Wada, Y., Kastner, T., and Puma, M. J. (2017). Groundwater depletion embedded in international food trade. Nature, 543(7647):700–704.

Dangar, S., Asoka, A., and Mishra, V. (2021). Causes and implications of groundwater depletion in india: A review. Journal of Hydrology, 596:126103.

Dangar, S. and Mishra, V. (2021). Natural and anthropogenic drivers of the lost groundwater from the ganga river basin. Environmental Research Letters, 16(11):114009.

Dangar, S. and Mishra, V. (2023). Excessive pumping limits the benefits of a strengthening summer monsoon for groundwater recovery in india. One Earth, 6(4):419–427.

de Graaf, I. E. M., Gleeson, T., van Beek, L. P. H. R., Sutanudjaja, E. H., and Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. Nature, 574(7776):90–94.

Devanand, A., Huang, M., Ashfaq, M., Barik, B., and Ghosh, S. (2019). Choice of Irrigation Water Management Practice Affects Indian Summer Monsoon Rainfall and Its Extremes. Geophysical Research Letters, 46(15):9126–9135.

Dhar, O. N. and Nandargi, S. (2003). Hydrometeorological aspects of floods in India. Natural Hazards, 28(1):1–33.

Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina (2021). Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change . Technical report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fenton, A., Paavola, J., and Tallontire, A. (2017). The role of microfinance in household livelihood adaptation in satkhira district, southwest bangladesh. World Development, 92:192–202.

Ferdous, M. R., Di Baldassarre, G., Brandimarte, L., and Wesselink, A. (2020). The interplay between structural flood protection, population density, and flood mortality along the jamuna river, bangladesh. Regional Environmental Change, 20:1–9.

Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary, A. A., Buettner, A., Hippler, D., and Matter, A. (2007). Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quaternary Science Reviews, 26(1-2):170–188.

Ganguly, D., Rasch, P. J., Wang, H., Yoon, J.-H., Ganguly, C. ., Rasch, P. J., Wang, H., and Yoon, J.-H. (2012). Climate response of the South Asian monsoon system to anthropogenic aerosols. Journal of Geophysical Research: Atmospheres, 117(D13):13209.

Gardelle, J., Berthier, E., and Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. Nature Geoscience 2012 5:5, 5(5):322–325.

Garg, S. and Mishra, V. (2019). Role of extreme precipitation and initial hydrologic conditions on floods in godavari river basin, india. Water Resources Research, 55(11):9191–9210.

Giorgi, F., Raffaele, F., and Coppola, E. (2019). The response of precipitation characteristics to global warming from climate projections. Earth System Dynamics, 10(1):73–89.

Gleeson, T., Cuthbert, M., Ferguson, G., and Perrone, D. (2020). Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. Annual Review of Earth and Planetary Sciences, 48(1).

Gleeson, T., Wada, Y., Bierkens, M. F. P., and van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. Nature, 488(7410):197–200.

Good, S. P., Noone, D., and Bowen, G. (2015). Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science, 349(6244):175–177.

Goswami, B. N., Venugopal, V., Sangupta, D., Madhusoodanan, M. S., and Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. Science, 314(5804):1442–1445.

Green, J. K., Seneviratne, S. I., Berg, A. M., Findell, K. L., Hagemann, S., Lawrence, D. M., and Gentine, P. (2019). Large influence of soil moisture on long-term terrestrial carbon uptake. Nature 2019 565:7740, 565(7740):476–479.

Guimberteau, M., Laval, K., Perrier, A., and Polcher, J. (2012). Global effect of irrigation and its impact on the onset of the Indian summer monsoon. Climate Dynamics, 39(6):1329–1348.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S. (2013). Global flood risk under climate change. Nature Climate Change 2013 3:9, 3(9):816–821.

Hovenden, M. J., Newton, P. C. D., and Wills, K. E. (2014). Seasonal not annual rainfall determines grassland biomass response to carbon dioxide. Nature, 511(7511):583–586.

Huss, M. and Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change 2018 8:2, 8(2):135–140.

Immerzeel, W. W. and Bierkens, M. F. P. (2012). Asia's water balance. Nature Geoscience, 5(12):841–842.

Jin, Q. and Wang, C. (2017). A revival of Indian summer monsoon rainfall since 2002. Nature Climate Change 2017 7:8, 7(8):587–594.

Kapnick, S. B., Delworth, T. L., Ashfaq, M., Malyshev, S., and Milly, P. C. (2014). Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle. Nature Geoscience 2014 7:11, 7(11):834–840.

Kishtawal, C., Jaiswal, N., Singh, R., and Niyogi, D. (2012). Tropical cyclone intensification trends during satellite era (1986–2010). Geophysical Research Letters, 39(10).

Kraaijenbrink, P. D., Bierkens, M. F., Lutz, A. F., and Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. Nature 2017 549:7671, 549(7671):257–260.

Kripalani, R. H. and Kumar, P. (2004). Northeast monsoon rainfall variability over south peninsular India vis-`a-vis the Indian Ocean dipole mode. International Journal of Climatology, 24(10):1267–1282.

Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., Turner, A. G., Slingo, J. M., and Rajendran, K. (2013). Will the South Asian monsoon overturning circulation stabilize any further? Climate Dynamics, 40(1-2):187–211.

Krishnan, R., Sabin, T. P., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B. N., Hourdin, F., Dufresne, J. L., and Terray, P. (2016). Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. Climate Dynamics, 47(3-4):1007–1027.

Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A., and Chakraborty, S. (2020). Assessment of climate change over the Indian region. A Report of the Ministry of Earth Sciences (MoES), Government of India, pages 1–226.

Kulkarni, A., Sabin, T. P., Chowdary, J. S., KoteswaraRao, K., Priya, P., Gandhi, N., Bhaskar, P., Buri, V. K., and Sabade, S. S. (2020). Precipitation changes in India. Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India, pages 47–72.

Kumar, R. and Mishra, V. (2020). Increase in Population Exposure Due to Dry and Wet Extremes in India Under a Warming Climate. Earth's Future.

Kushwaha, A. P., Tiwari, A. D., Dangar, S., Shah, H., Mahto, S. S., and Mishra, V. (2021). Multimodel assessment of water budget in Indian sub-continental river basins. Journal of Hydrology, 603.

Loon, A. F. V., Gleeson, T., Clark, J., Dijk, A. I. J. M. V., Stahl, K., Hannaford, J., Baldassarre, G. D., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and Lanen, H. A. J. V. (2016). Drought in the Anthropocene. Nature Geoscience.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., and Bierkens, M. F. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change 2014 4:7, 4(7):587–592.

Lutz, A. F., ter Maat, H. W., Wijngaard, R. R., Biemans, H., Syed, A., Shrestha, A. B., Wester, P., and Immerzeel, W. W. (2019). South Asian river basins in a 1.5 °C warmer world. Regional Environmental Change, 19(3):833–847.

MacDonald, A. M., Bonsor, H. C., Ahmed, K. M., Burgess, W. G., Basharat, M., Calow, R. C., Dixit, A., Foster, S. S. D., Gopal, K., Lapworth, D. J., Lark, R. M., Moench, M., Mukherjee, A., Rao, M. S., Shamsudduha, M., Smith, L., Taylor, R. G., Tucker, J., van Steenbergen, F., and Yadav, S. K. (2016). Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nature Geoscience, 9(10):762–766.

Mahto, S. S. and Mishra, V. (2020). Dominance of summer monsoon flash droughts in India. Environmental Research Letters.

Mali, S. S., Shirsath, P. B., and Islam, A. (2021). A high-resolution assessment of climate change impact on water footprints of cereal production in India. Scientific Reports, 11(1):8715.

Mallya, G., Mishra, V., Niyogi, D., Tripathi, S., and Govindaraju, R. S. (2016). Trends and variability of droughts over the indian monsoon region. Weather and Climate Extremes, 12:43–68.

Mathur, R. and AchutaRao, K. (2019). A modelling exploration of the sensitivity of the India's climate to irrigation. Climate Dynamics 2019 54:3, 54(3):1851–1872.

Maurer, J. M., Schaefer, J. M., Rupper, S., and Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. Science Advances, 5(6).

Menon, A., Levermann, A., Schewe, J., Lehmann, J., and Frieler, K. (2013). Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models. Earth System Dynamics, 4(2):287–300.

Mishra, A. K. and Singh, V. P. (2010). A review of drought concepts. Journal of Hydrology, 391(1-2):202–216.

Mishra, V. (2020). Long-term (1870–2018) drought reconstruction in context of surface water security in India. Journal of Hydrology, 580:124228.

Mishra, V., Aadhar, S., Asoka, A., Pai, S., and Kumar, R. (2016). On the frequency of the 2015 monsoon season drought in the Indo-Gangetic Plain. Geophysical Research Letters, 43(23):12, 102–112, 112.

Mishra, V., Asoka, A., Vatta, K., and Lall, U. (2018). Groundwater Depletion and Associated CO 2 Emissions in India. Earth's Future, 6(12):1672–1681.

Mishra, V. and Lilhare, R. (2016). Hydrologic sensitivity of Indian sub-continental river basins to climate change. Global and Planetary Change, 139:78–96.

Mishra, V. and Shah, H. L. (2018). Hydroclimatological perspective of the kerala flood of 2018. Journal of the Geological Society of India, 92:645–650.

Mishra, V., Shah, R., and Thrasher, B. (2014). Soil moisture droughts under the retrospective and projected climate in India. Journal of Hydrometeorology, 15(6):2267–2292.

Mishra, V., Smoliak, B. V., Lettenmaier, D. P., and Wallace, J. M. (2012). A prominent pattern of year-to-year variability in Indian Summer Monsoon Rainfall. Proceedings of the National Academy of Sciences of the United States of America, 109(19):7213–7217.

Mishra, V., Thirumalai, K., Jain, S., and Aadhar, S. (2021). Unprecedented drought in South India and recent water scarcity. Environmental Research Letters, 16(5):054007.

Mishra, V., Thirumalai, K., Singh, D., and Aadhar, S. (2020). Future exacerbation of hot and dry summer monsoon extremes in India. npj Climate and Atmospheric Science 2020 3:1, 3(1):1–9.

Mukherjee, S., Aadhar, S., Stone, D., and Mishra, V. (2018a). Increase in extreme precipitation events under anthropogenic warming in India. Weather and Climate Extremes, 20:45–53.

Mukherjee, A., Bhanja, S. N., and Wada, Y. (2018b). Groundwater depletion causing reduction of baseflow triggering Ganges river summer drying. Scientific Reports, 8(1):12049.

Nageswararao, M. M., Sannan, M. C., and Mohanty, U. C. (2019). Characteristics of various rainfall events over South Peninsular India during northeast monsoon using high-resolution gridded dataset (1901–2016). Theoretical and Applied Climatology, 137(3-4):2573–2593.

Najibi, N. and Devineni, N. (2018). Recent trends in the frequency and duration of global floods. Earth System Dynamics, 9(2):757–783.

Nanditha, J. S. and Mishra, V. (2022). Multiday Precipitation Is a Prominent Driver of Floods in Indian River Basins. Water Resources Research, 58(7):e2022WR032723.

Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K., and Chen, X. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. Nature Reviews Earth & Environment 2021 2:2,2(2):91–106.

Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., and Song, C. (2017). A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. Remote Sensing of Environment, 189:1–13.

Niyogi, D., Subramanian, S., Mohanty, U. C., Kishtawal, C. M., Ghosh, S., Nair, U. S., Ek, M., and Rajeevan, M. (2018). The Impact of Land Cover and Land Use Change on the Indian Monsoon Region Hydroclimate. pages 553–575.

Noska, R. and Misra, V. (2016). Characterizing the onset and demise of the Indian summer monsoon. Geophysical Research Letters, 43(9):4547–4554.

Padmakumari, B., Jaswal, A. K., and Goswami, B. N. (2013). Decrease in evaporation over the Indian monsoon region: Implication on regional hydrological cycle. Climatic Change, 121(4):787–799.

Pai, D., Sridhar, L., Guhathakurta, P., and Hatwar, H. (2011). District-wide drought climatology of the southwest monsoon season over india based on standardized precipitation index (spi). Natural hazards, 59:1797–1813.

Pai, D. S., Guhathakurta, P., Kulkarni, A., and Rajeevan, M. N. (2017). Variability of Meteorological Droughts Over India. Springer Geology, pages 73–87.

Panda, D. K. and Wahr, J. (2016). Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records. Water Resources Research, 52(1):135–149.

Pant, N. C., Ravindra, R., Srivastava, D., and Thompson, L. (2018). The Himalayan cryosphere: Past and present variability of the ’third pole’. Geological Society Special Publication, 462(1):1–6

Paul, S., Ghosh, S., Mathew, M., Devanand, A., Karmakar, S., and Niyogi, D. (2018). Increased Spatial Variability and Intensification of Extreme Monsoon Rainfall due to Urbanization. Scientific Reports 2018 8:1, 8(1):1–10.

Penny, G., Srinivasan, V., Apoorva, R., Jeremiah, K., Peschel, J., Young, S., and Thompson, S. (2020). A process-based approach to attribution of historical streamflow decline in a data-scarce and human-dominated watershed. Hydrological Processes, 34(8):1981–1995.

Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D., Miller, J. R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Sch¨oner, W., Severskiy, I., Shahgedanova, M., Wang, M. B., Williamson, S. N., and Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. Nature Climate Change 2015 5:5, 5(5):424–430.

Pervez, M. S. and Henebry, G. M. (2015). Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin. Journal of Hydrology: Regional Studies, 3:285–311.

Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. Nature 2019 569:7758, 569(7758):649–654.

Rajeev, A. and Mishra, V. (2023). Increasing risk of compound wind and precipitation extremes due to tropical cyclones in India. Environmental Research: Climate, 2(2):021004.

Rajeevan, M., Unnikrishnan, C. K., Bhate, J., Niranjan Kumar, K., and Sreekala, P. P. (2012). Northeast monsoon over India: variability and prediction. Meteorological Applications, 19(2):226–236.

Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. Nature Geoscience 2008 1:4, 1(4):221–227.

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., and Lo, M.-H. H. (2018). Emerging trends in global freshwater availability. Nature, 557(7707):651–659.

Rodell, M., Velicogna, I., and Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. Nature, 460(7258):999–1002.

Rosa, L., Chiarelli, D. D., Rulli, M. C., Dell'Angelo, J., and D'Odorico, P. (2020). Global agricultural economic water scarcity. Science Advances, 6(18):1–11.

Rosenzweig, C., Solecki, W., Hammer, S. A., and Mehrotra, S. (2010). Cities lead the way in climate–change action. Nature 2010 467:7318, 467(7318):909–911.

Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., and Rajeevan, M. (2017). A threefold rise in widespread extreme rain events over central India. Nature Communications, 8(1):1–12

Roxy, M. K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., and Goswami, B. N. (2015). Drying of Indian subcontinent by rapid Indian ocean warming and a weakening land-sea thermal gradient. Nature Communications, 6(1):1–10.

Saha, A., Ghosh, S., Sahana, A. S., and Rao, E. P. (2014). Failure of CMIP5 climate models in simulating post-1950 decreasing trend of Indian monsoon. Geophysical Research Letters, 41(20):7323–7330.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colˊon-Gonzˊalez, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., and Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences of the United States of America, 111(9):3245–3250.

Schwanghart, W., Worni, R., Huggel, C., Stoffel, M., and Korup, O. (2016). Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods. Environmental Research Letters, 11(7):074005.

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

Shah, H. and Mishra, V. (2018). Climate Change Impacts on Streamflow in India.

Shah, H. L. and Mishra, V. (2016). Hydrologic changes in Indian subcontinental river basins (1901-2012). Journal of Hydrometeorology, 17(10):2667–2687.

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. Environmental Research Letters, 4(3).

Sharma, A., Wasko, C., and Lettenmaier, D. P. (2018). If precipitation extremes are increasing, why aren't floods? Water resources research, 54(11):8545–8551.

Sharma, S. and Mujumdar, P. (2017). Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. Scientific Reports, 7(1):15582.

Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A., and Osmanoglu, B. (2020). A Systematic, Regional Assessment of High Mountain Asia Glacier Mass Balance. Frontiers in Earth Science, 7:363.

Shrestha, A. B., Agrawal, N. K., Alfthan, B., Bajracharya, S. R., Mar´echal, J., Oort, B. v., et al. (2015). The himalayan climate and water atlas: impact of climate change on water resources in five of asia's major river basins. The Himalayan Climate and Water Atlas: impact of climate change on water resources in five of Asia's major river basins.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., D¨oll, P., and Portmann, F. T. (2010). Groundwater use for irrigation – a global inventory. Hydrology and Earth System Sciences, 14(10):1863–1880.

Singh, D., Ghosh, S., Roxy, M. K., and McDermid, S. (2019). Indian summer monsoon: Extreme events, historical changes, and role of anthropogenic forcings. Wiley Interdisciplinary Reviews: Climate Change, 10(2):e571.

Singh, R. and AchutaRao, K. (2019). Quantifying uncertainty in twenty-first century climate change over India. Climate Dynamics, 52(7-8):3905–3928.

Sinha, N., Gandhi, N., Chakraborty, S., Krishnan, R., Yadava, M. G., and Ramesh, R. (2018). Abrupt climate change at ˜2800 yr BP evidenced by a stalagmite record from peninsular India. https://doi.org/10.1177/0959683618788647, 28(11):1720–1730.

Skinner, C. B., Poulsen, C. J., Chadwick, R., Diffenbaugh, N. S., and Fiorella, R. P. (2017). The Role of Plant CO2 Physiological Forcing in Shaping Future Daily-Scale Precipitation. Journal of Climate, 30(7):2319–2340.

Sun, D., Yang, H., Guan, D., Yang, M., Wu, J., Yuan, F., Jin, C., Wang, A., and Zhang, Y. (2018). The effects of land use change on soil infiltration capacity in China: A meta-analysis. Science of The Total Environment, 626:1394–1401.

Thiery, W., Visser, A. J., Fischer, E. M., Hauser, M., Hirsch, A. L., Lawrence, D. M., Lejeune, Q., Davin, E. L., and Seneviratne, S. I. (2020). Warming of hot extremes alleviated by expanding irrigation. Nature Communications 2020 11:1, 11(1):1–7.

Tiwari, V. M., Wahr, J., and Swenson, S. (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. Geophysical Research Letters, 36(18):L18401.

Van Oldenborgh, G. J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., and Cullen, H. (2017). Attribution of extreme rainfall from hurricane harvey, august 2017. Environmental Research Letters, 12(12):124009.

Vellore, R. K., Kaplan, M. L., Krishnan, R., Lewis, J. M., Sabade, S., Deshpande, N., Singh, B. B., Madhura, R., and Rama Rao, M. (2016). Monsoon-extratropical circulation interactions in himalayan extreme rainfall. Climate Dynamics, 46:3517–3546.

Ward, P. J., Kummu, M., and Lall, U. (2016). Flood frequencies and durations and their response to El Nĩno Southern Oscillation: Global analysis. Journal of Hydrology, 539:358–378.

Wasko, C., Nathan, R., and Peel, M. C. (2020). Changes in Antecedent Soil Moisture Modulate Flood Seasonality in a Changing Climate. Water Resources Research, 56(3):e2019WR026300.

Wijngaard, R. R., Lutz, A. F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. B., and Immerzeel, W. W. (2017). Future changes in hydro-climatic extremes in the upper indus, ganges, and brahmaputra river basins. PloS one, 12(12):e0190224.

Wu, W. Y., Lo, M. H., Wada, Y., Famiglietti, J. S., Reager, J. T., Yeh, P. J. F. F., Ducharne, A., and Yang, Z. L. (2020). Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. Nature Communications, 11(1):1–9.

Xu, C., Sano, M., and Nakatsuka, T. (2013). A 400-year record of hydroclimate variability and local ENSO history in northern Southeast Asia inferred from tree-ring δ 18O. Palaeogeography, Palaeoclimatology, Palaeoecology, 386:588–598

Zaherpour, J., Gosling, S. N., Mount, N., Schmied, H. M., Veldkamp, T. I. E., Dankers, R., Eisner, S., Gerten, D., Gudmundsson, L., Haddeland, I., Hanasaki, N., Kim, H., Leng, G., Liu, J., Masaki, Y., Oki, T., Pokhrel, Y., Satoh, Y., Schewe, J., and Wada, Y. (2018). Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. Environmental Research Letters, 13(6).

Zaveri, E., Grogan, D. S., Fisher-Vanden, K., Frolking, S., Lammers, R. B., Wrenn, D. H., Prusevich, A., and Nicholas, R. E. (2016). Invisible water, visible impact: Groundwater use and Indian agriculture under climate change. Environmental Research Letters,11(8):84005.

Zeng, Z., Piao, S., Li, L. Z., Wang, T., Ciais, P., Lian, X., Yang, Y., Mao, J., Shi, X., and Myneni, R. B. (2018). Impact of Earth Greening on the Terrestrial Water Cycle. Journal of Climate, 31(7):2633–2650.

Zhou, S., Park Williams, A., Berg, A. M., Cook, B. I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S. I., and Gentine, P. (2019). Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. Proceedings of the National Academy of Sciences of the United States of America, 116(38):18848–18853.

Zhu, Z., Piao, S., Myneni, R. B., Huang, M., Zeng, Z., Canadell, J. G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peuelas, J., Poulter, B., Pugh, T. A., Stocker, B. D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., and Zeng, N. (2016). Greening of the Earth and its drivers. Nature Climate Change 2016 6:8, 6(8):791–795

CHAPTER 8: CARBON CYCLE

Manish K Goyal and Subimal Ghosh

Coordinating Lead Author
Prof. Manish K Goyal, IIT Indore

Lead Authors
Prof. Subimal Ghosh, IIT Bombay

BACKGROUND

The processes of the carbon cycle are key to the functioning of life supporting systems and are inextricably linked to the climate of our planet. Carbon is constantly cycling between the reserves in the atmosphere, ocean, and on land (Figure 8.1). Prior to human interference with the environment, the amount of carbon released by natural processes (such as the decomposition of organic matter) was roughly equal to the amount of carbon absorbed (for example, by vegetation growth), resulting in an atmospheric CO_2 concentration that has been relatively stable since the end of the last glaciation 10,000 years ago (Gasser et al., 2020; Joos & Spahni, 2008).

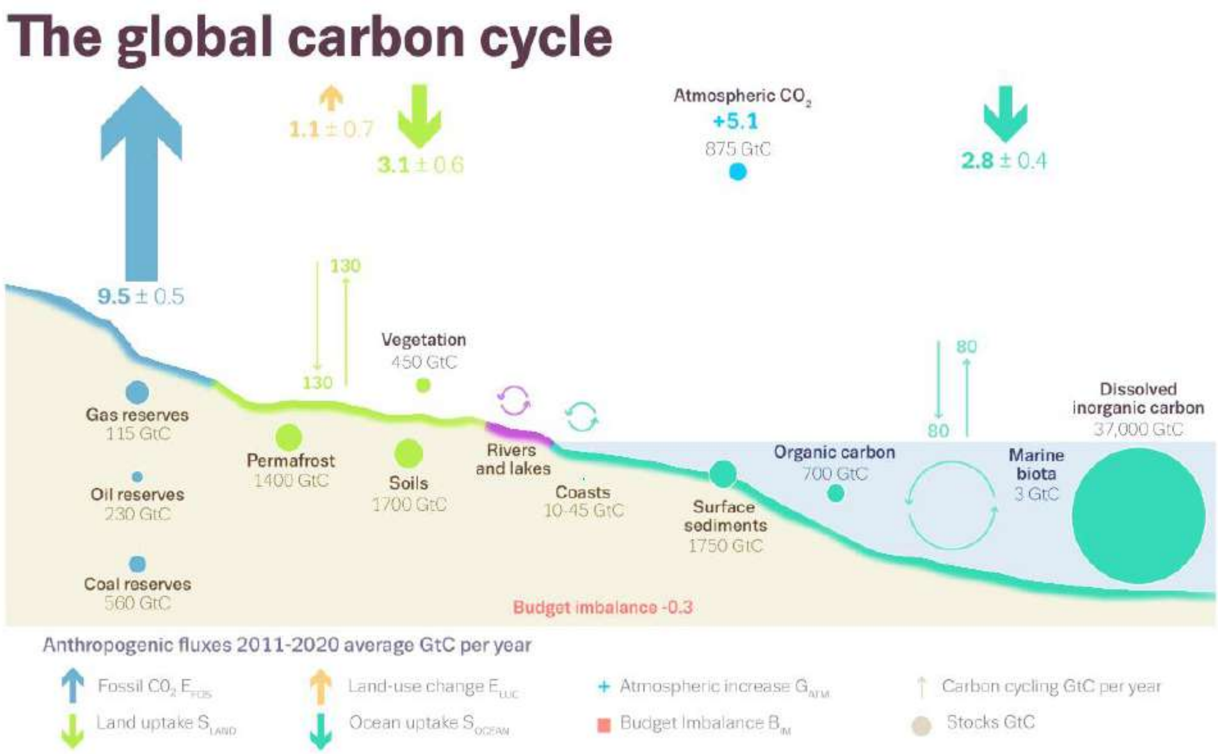


Figure 8.1: Schematic depiction of the entire disruption to the carbon cycle brought on by human activity, averaged globally for the decade 2011–2020. Take reference of legends for the corresponding arrows and units. Because of its small magnitude, the figure ignores the uncertainty in the rate of atmospheric CO_2 rise [Source: (Friedlingstein et al., 2022)].

The relatively steady surface air temperature sustained for long because of the balanced carbon cycle between its pools and fluxes. The degree of changing global climate had impacted the carbon cycle proportionately and vice versa and likely to cause disturbance to its mutual fragile equilibrium. The history of Earth with cold and warm periods has demonstrated how natural disturbances, such as glaciations, brought on by changes to the axial tilt and orbit of the planet, can disrupt the carbon cycle, altering the amount of CO_2 in the atmosphere and other reservoirs with consequences for the climate change (Houghton & Nassikas, 2017). Such natural variations highlight the complexities of interrelationships and feedbacks between the carbon cycle and climate system. The atmospheric CO_2 content has risen quickly due to the accelerated rates of anthropogenic emissions to levels unprecedented in the last three million years (Canadell et al., 2022). The carbon cycle through its natural sinks, absorbs smaller proportion of these emissions and as result it has significantly disrupted the fragile balance much beyond the normal oscillations. Therefore, a deeper understanding of the sub systems of carbon cycle is necessary in order to predict future climate change.

Climate scenarios are projections of future climate conditions based on different sets of assumptions about future human activities and greenhouse gas emissions. The most commonly used frameworks for developing these scenarios are the Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs). RCPs describe different trajectories of atmospheric greenhouse gas concentrations based on varying levels of human activity and economic development. They are based on four different pathways: RCP2.6, RCP4.5, RCP6, and RCP8.5, each representing a different level of greenhouse gas emissions and atmospheric concentrations. RCP2.6 represents the lowest emissions scenario, while RCP8.5 represents the highest. SSPs provide a range of plausible social and economic outcomes that can be used to develop scenarios for emissions and other factors affecting climate change. The SSPs are based on five different scenarios: SSP1, SSP2, SSP3, SSP4, and SSP5, each representing a different combination of social, economic, and technological developments. Together, RCPs and SSPs are important tools for understanding the potential impacts of climate change and for guiding efforts to mitigate and adapt to these impacts. They are used in climate models to project future temperature, precipitation, sea level rise, and other climate-related variables, and are important inputs for decision-making related to climate policy, infrastructure planning, and adaptation planning.

It is indisputably true that the increase in atmospheric CO_2 since 1750 is resulting from direct emissions from human activities and is evident through multiple lines of evidence using isotopes, interhemispheric gradients of CO_2 concentrations, and inventory data. Carbon sinks on land and in the oceans help to contain the atmospheric rise of CO_2. Projections reveal that, even if the natural sinks (land and ocean) absorb more CO_2 in high-emission scenarios in comparison with low-emission scenarios, the fraction of emissions removed from the atmosphere by natural sinks declines with higher concentrations (high confidence) (IPCC, 2021). Physical ocean and biospheric land processes that promote the movement of carbon across various land, ocean, and atmospheric reservoirs are primarily linked to carbon sinks for anthropogenic CO_2. These exchanges are influenced by changing climate but are driven by rising atmospheric CO_2. As per recent report by IPCC (2021), for the years 1750 to 2019, the combustion of fossil fuels and changes in land use led to the release of 700 PgC (with uncertainty of 75 PgC) of which 41% (with uncertainty of 11%) is still present in the atmosphere today (high confidence) [1 PgC is equivalent to 10^{15} g of carbon]. Around 64% (with uncertainty of 15%) of the total anthropogenic CO_2 emissions were attributable to the burning of fossil fuels; over the last 10 years, this percentage has increased to 86% (with uncertainty of 14%). The remaining was the result of the emission from land use change. Anthropogenic CO_2 emissions peaked at 10.9 PgC per year (with uncertainty of 0.9 PgC per year) between 2010-2019, the highest yearly average levels ever recorded in human history (high confidence) (Figure 8.2). 46% of these emissions were absorbed by the atmosphere (5.1 PgC per year with uncertainty of 0.02 PgC per year), 23% by the ocean (2.5 PgC per year with uncertainty of 0.6 PgC per year), and 31% by terrestrial ecosystems (3.4 PgC per year with uncertainty of 0.9 PgC per year) respectively (high confidence) (Figure 8.2) (IPCC, 2021).

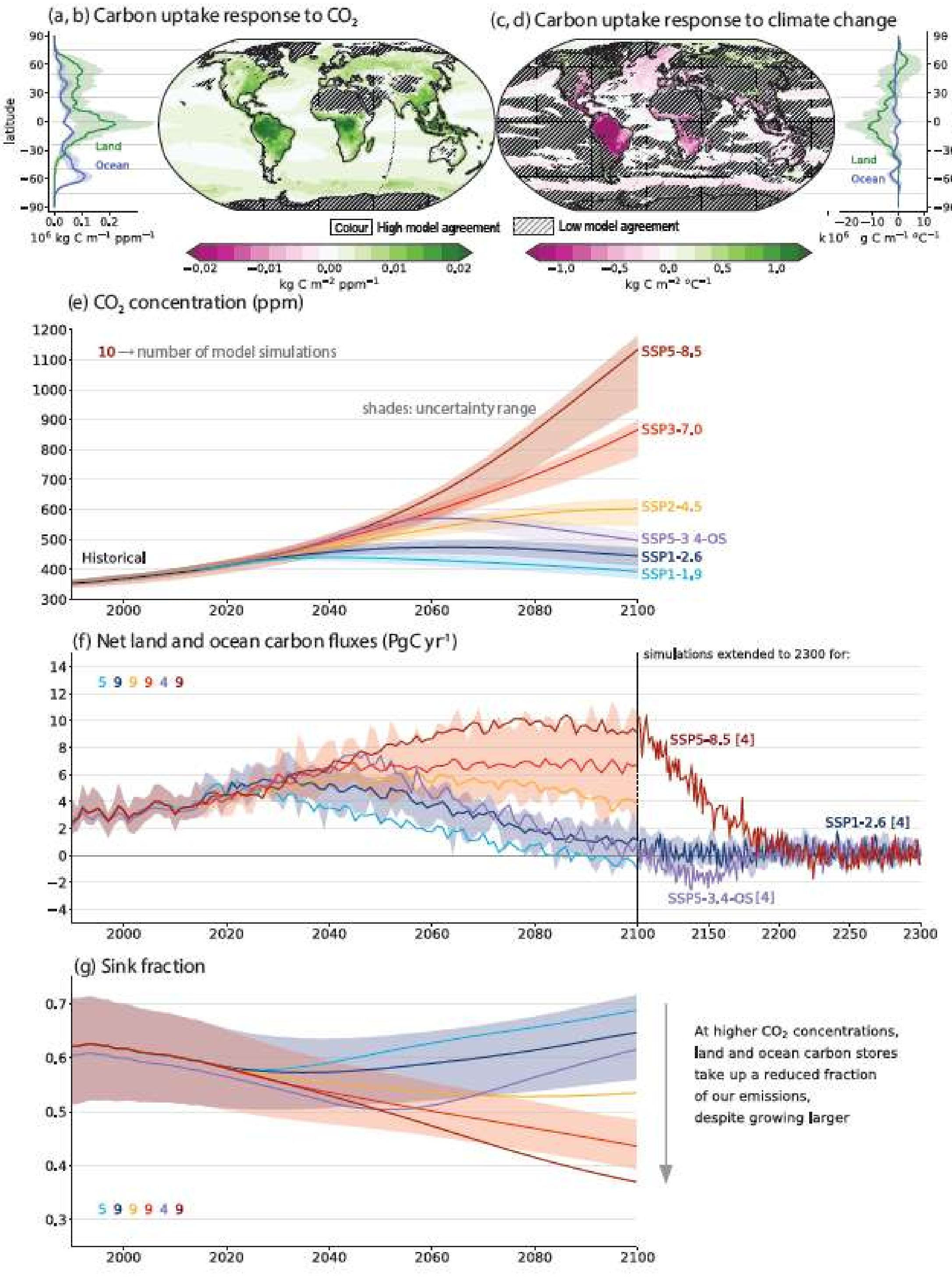


Figure 8.2: Process and projections of carbon cycle: (a, b) Carbon uptake response to climate warming; (c, d) Carbon uptake response to climate change; (e) CO2 concentration in ppm in different

scenarios; (f) Net land and ocean carbon fluxes (in PgC per year); (g) Sink fraction. [IPCC WG I, Climate Change 2021: The Physical Science Basis, carbon cycle]

Over the past 60 years, anthropogenic emissions have led to a rise in the land and ocean CO_2 sinks (high confidence). The atmospheric portion of anthropogenic CO_2 has remained about 44% (with uncertainty of 10%) throughout the past 60 years due to the coherence between emissions and the growth in ocean and land sinks (high confidence). The decadal and interannual variability of the ocean and terrestrial sinks reveals that they are sensitive to changes in the rate of emissions growth as well as climate variability, and as a result, they are also vulnerable to climate change (high confidence) (IPCC, 2021).

Also, carbon as an essential material component plays an important role in a variety of processes related to social, biological, physical, and infrastructural sectors, including croplands, grasslands, forests, industry, buildings, and other constructions. Carbon-based fuels are mostly burned to provide energy, but people also utilize carbon in various other pathways, such as in food and buildings.

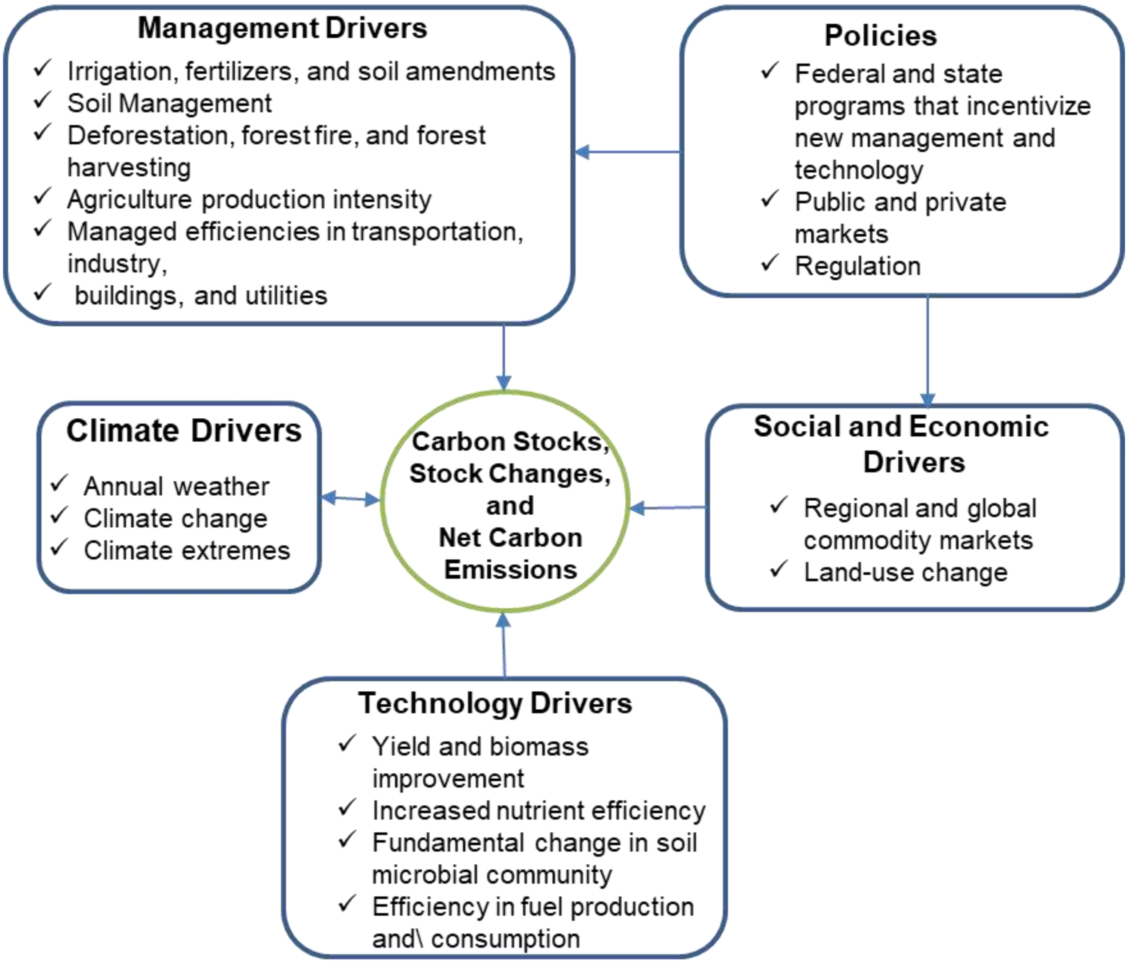


Figure 8.3: This schematic demonstration of various components representing carbon stock changes to understand and estimate future carbon stocks and emissions

All components of the carbon cycle interact intricately with one another as well as with society and the environment in ways that are not completely understood. Given this complexity, a systems approach may be extremely helpful in discovering strategies to lower atmospheric carbon emissions.

As illustrated in figure 8.3, such an approach takes a complete, holistic, and multidisciplinary approach at carbon and takes into account social, economic, and environmental concerns.

The "India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change" provides an overview of India's efforts to address climate change and its progress towards meeting its commitments under the Convention. The report highlights India's ambitious targets to reduce emissions intensity of GDP by 33-35% by 2030, increase the share of non-fossil fuels in its energy mix to 40% by 2030, and create an additional carbon sink of 2.5-3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030. The report also discusses the measures India has taken to reduce emissions, including the promotion of renewable energy, energy efficiency, and sustainable transport. The report emphasizes the role of innovation and technology in achieving these goals, including the development of a national wind-solar hybrid policy and the introduction of electric vehicles in various cities. In addition, the report highlights the challenges India faces in addressing climate change, including its vulnerability to the impacts of climate change and the need for international cooperation to mobilize financial and technological support for climate action.

Objectives

1. Assessment of annual carbon budget:

It will accomplish two things.

First, there is a high requirement for recent evidence on the status of anthropogenic climate disruption and its underlying causes. The datasets connected with the annual carbon budget are used by many stakeholders, including scientists, policymakers, corporations, journalists, and non-governmental groups working to adapt to and mitigate human-driven climate change.

Second, the human and biophysical environments have undergone unprecedented changes in recent decades, necessitating regular assessments of the state of the planet, better quantification of the reasons behind shifts in the present global carbon cycle, and a better ability to predict its future evolution.

2. Building scientific understanding to address the unprecedented climate mitigation challenge that necessitates frequent, rigorous, transparent, and traceable datasets and methodologies that can be reviewed and imitated.

3. Creating national-level vegetation productivity data considering meteorology and carbon fertilization.

4. Estimating carbon uptake potential of Indian forests and intensified agriculture as well as predicting the trajectory in a warming climate.

5. Introducing a road-map focusing on short-term goals at various scales to achieve long-term targets on establishing balance over the global carbon budget.

ROADMAP-SHORT-TERM (BY 2030)

Roadmaps are planning methods, involving short-term goals to long-term goals. These help to support the administrations to initiate technical and functional innovations to meet a combined challenge. An obvious carbon roadmap for reducing anthropogenic effects each decade, intended with the industrial sectors, might improve to promote disrupting, nonlinear technological innovations on the way to a zero-emissions globe (Figure 8.4).

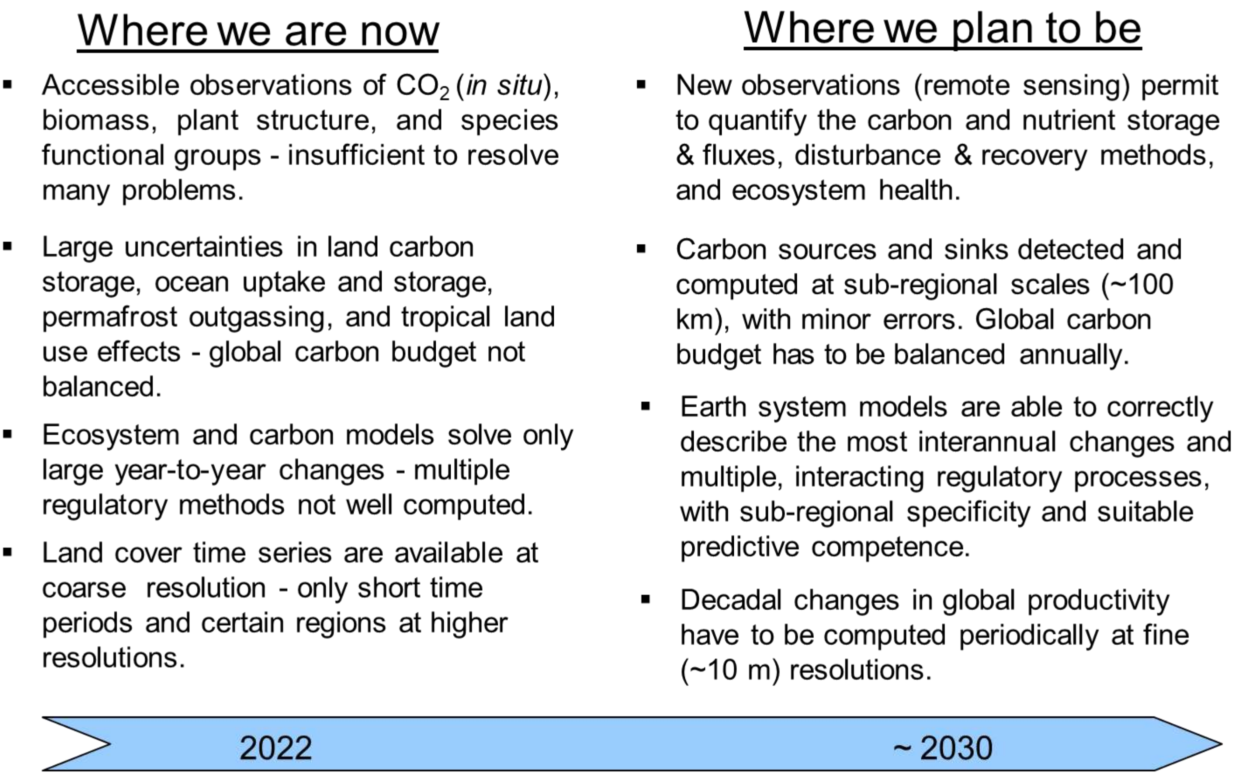


Figure 8.4. Anticipated progress for carbon cycle by the year 2030

There is a need of an emerging quantifiable scientific data, robust observations, and models to establish the emissions and understanding of CO, CO_2, and CH_4, changes in carbon stocks, and the factors controlling these activities (Figure 8.5). Research must provide for a long-term quantifiable measurement of fluxes, sources, and sinks of atmospheric CO_2 and CH_4, and improve predictions for future trends. Further, developing the methodical approach to execute complete carbon reporting on regional and international levels.

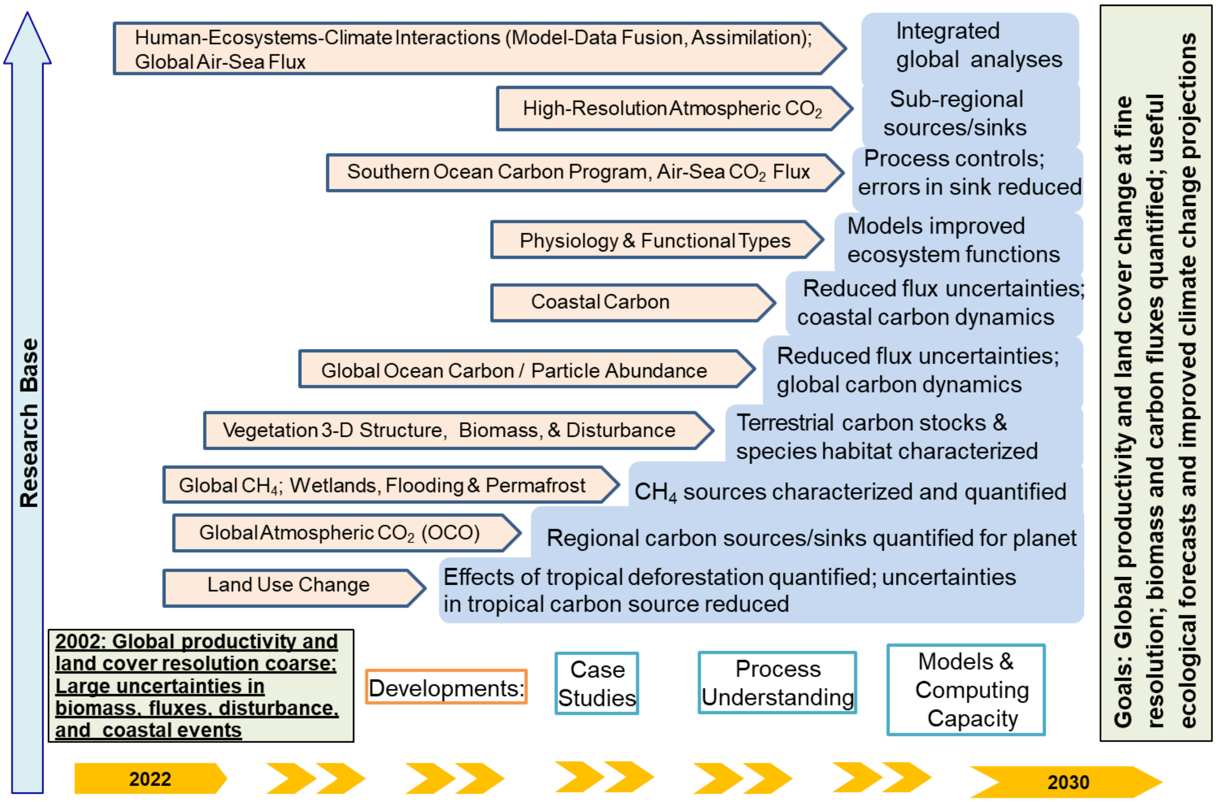


Figure 8.5. Detailed roadmap for carbon cycle by the year 2030

Example of an approach

An investment for climate solutions should expand in research and development (R&D) by the year 2030. Using different scientific methods, we can provide daily to annual assessment of carbon stocks and fluxes by developing model structure. For example, an order of remote sensing and field observations should use for model testing and advancement of data integration techniques (Figure 8.6).

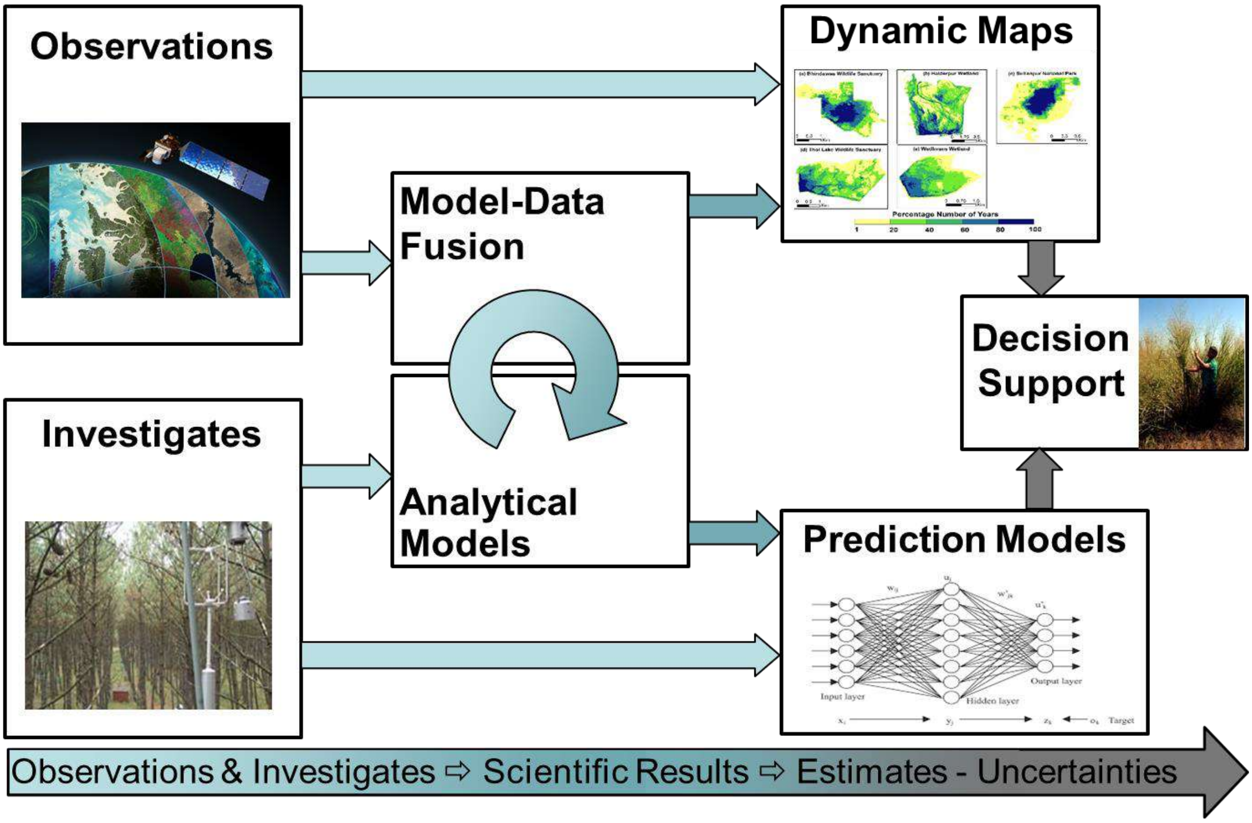


Figure 8.6. Example of an approach used for decision support system

REFERENCES

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., C. P. M., Eliseev, A. v., et al. (2022). Global Carbon and other Biogeochemical Cycles and Feedbacks, in: Climate Change 2021: The Physical Science Basis. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Dlugokencky, E., & Tans, P. (2022, November 11). Trends in atmospheric carbon dioxide.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., et al. (2022). Global Carbon Budget 2021. *Earth System Science Data*, *14*(4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R. A., Ciais, P., & Obersteiner, M. (2020). Historical CO2 emissions from land use and land cover change and their uncertainty. *Biogeosciences*, *17*(15), 4075–4101. https://doi.org/10.5194/bg-17-4075-2020

Houghton, R. A., & Nassikas, A. A. (2017). Global and regional fluxes of carbon from land use and land cover change 1850-2015. *Global Biogeochemical Cycles*, *31*(3), 456–472. https://doi.org/10.1002/2016GB005546

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Joos, F., & Spahni, R. (2008). Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *Proceedings of the National Academy of Sciences*, *105*(5), 1425–1430. https://doi.org/10.1073/pnas.0707386105

CHAPTER 9: SECTOR-SPECIFIC CLIMATE SERVICES

V Geethalakshmi, Manish K Goyal, Udit Bhatia, Sagnik Dey, S A Sannasiraj, Ashwin K Seshadri, Subhankar Karmakar, Anil Kumar Gupta, Rajib Chattopadhyay, K S Hosalikar

Coordinating Lead Author
Dr. K S Hosalikar, IMD Pune

Lead Authors
V Geethalakshmi, Tamil Nadu Agricultural University
Manish K Goyal, IIT Indore
Udit Bhatia, IIT Gandhinagar
Sagnik Dey, IIT Delhi
S A Sannasiraj, IIT Madras
Ashwin K Seshadri, IISc Bangalore
Subhankar Karmakar, IIT Bombay
Anil Kumar Gupta, National Institute of Disaster Management
Rajib Chattopadhyay, IMD Pune

Climate Services are the dissemination of climate information to the public or a specific user. They involve strong partnerships among providers and stakeholders, including government agencies, private interests, and academia, for the purpose of interpreting and applying climate information for decision making, sustainable development, and improving climate information products, predictions, and outlooks, as defined by the World Meteorological Organization (WMO).

PREFACE

Improving climate services and developing a better engagement with stakeholders is a priority area in recent times. The section is a compilation of contributions from several eminent researchers and professors working in different fields who use climate services in their day-to-day research and has contributed significantly in their respective field of research. The chapter summarizes near future vision documents for the application of climate services to various sectors: (i) Agriculture, (ii) Water, (iii) Disaster Risk Mitigation, (iv) Infrastructure resilience, (v) Health, (vi) Coastal Management and (viii) Renewable energy. Editors thankfully acknowledge the contributions from the authors who has developed the vision document in a comprehensive manner. While there is no dearth of technology and academic research, it is required that the research and technology are made available to the stakeholders in an appropriate manner. It is hoped that the conclave would provide a direction in implementation of synergistic mechanisms for the sectors mentioned above. It is also expected that the document would be useful for the researchers working in the above-mentioned field to develop several success stories in the field of application of climate services in the short and long-term.

INTRODUCTION

In recent decades climate services, in addition to weather services, play a significant role at the individual level and in the society facing new challenges to make improved ex-ante decision-making. The challenges now have become more critical which require deeper understanding in spite of availability of best research and technology. It is now understood that climate services are to be user and sector-specific for better response to user requirements in a seamless manner.

Weather services now a day's face challenge due to increased threat from climate change. From the perspective of "climate is what you expect and the weather is what you get", users of weather forecasts can benefit by using climate advisories by extending their forecast horizon. For most users the climate and weather information are complementary, hence they are to be used in tandem. From the Indian perspective, weather and climate services have developed for a period ranging ~150 years with the establishment of the India Meteorological Department and the subsequent establishment of other scientific departments that worked in a partnership mode to prepare the nation for all the weather and climate related challenges. Over the last few decades, the scope of application of climate services has expanded in leaps and bounds to meet the challenges and threats posed by climate change. United Nations has proposed sustainable development goals, that have led to the integration of climate services with societal development in a more target-oriented manner. The establishment of a "Global Framework for climate services " (GFCS) thrust to some priority areas e.g. agriculture, water, health, and energy has got momentum. Similarly, several countries have initiated "National Framework of Climate Services" to put the climate services in a better perspective. Over India, several initiatives are taken in this direction.

In the context of developing short to near-term object-oriented goals for climate services in the priority areas focused planning and research are a necessity. The chapter summarizes near future vision documents for the application of climate services to various sectors:

(i) Agriculture, (ii) Water, (iii) Disaster Risk Mitigation, (iv) Infrastructure resilience, (v) Health, (vi) Coastal Management and (viii) Renewable energy. The sectors mentioned above require climate information on various spatial and temporal scales, and the services can improve immensely with the improvement of climate services.

The agriculture sector highlighted the urgent requirement of improving the collaborative effort to develop and co-produce climate data relevant to the agricultural sector, the development of climate forecast to cater to the requirement of end users in a smooth way. In this context, this sector requires more digital innovation for the dissemination of climate services in near future.

The water sector documented the current water stress faced by several nations and has demonstrated the necessity of scientific water management in India. There are inextricable linkages between water, climate, and socio-economic sectors, i.e., ecosystems, human settlements, energy, agriculture and sanitation, and hygiene. The sustainable development goals (SDGs) associated with this sector can be archived through objective development and planning. The section stresses special monitoring of regional freshwater water resources and protection of regional water sources among other priorities. In future plan should aim to provide India-specific modelling through the integration of land surface models by including glacier components, Indian region-specific water management, crop practices, and coupling groundwater with lateral flows.

In the next section, the importance of climate services in disaster risk mitigation associated with hydro-climatic extreme events is discussed. the structural measures of disaster mitigation involve adaptive structural design, while the non-structural measures include improving forecasting, human capacities, policy planning, and promoting stakeholder-centric solutions. Climate models usually perform well except for extremes which is a major bottleneck in this direction. Improving extreme simulations and forecasts, using innovative solutions to make them stakeholder-centric, and designing climate adaptation strategies ought to be considered high-priority research areas.

The next section discusses the development of climate services focus sing on health sectors. Evidence of climate change impacts human health is unequivocal globally. According to the World Health Organization (WHO), nearly 23% of global deaths in 2012 were attributable to factors affected by climate variability. Changes in extreme weather events and gradual changes in weather and climatic conditions directly and indirectly (through environmental and ecological changes) impact physical and mental health. This sector requires customized climate products (e.g. downscaled climate information), and strengthen climate information-based disease risk management systems. This sector requires strong support from interdisciplinary research projects for a better understanding of the risks.

The next section describes the coastal management services. Climate service components can play a critical role in the development of monitoring of coastal climate, and ecosystem and can help in the development of coastal industries, protection of coral reefs, fishery management, coastal and inland shipping interconnectivity, etc.

Climate services can also play a crucial role in the development of the country's renewable resources. In the longer and shorter time scales, As India's renewable energy capacity grows in recent decades, weather and climate science will play a crucial role in energy-specific services, such as identification (site selection and capacity estimation), planning (storage assessment, transmission/distribution investments, ancillary infrastructure, insurance), and operations. On shorter timescales, electricity dispatch, unit commitment, and scheduling and pricing depend on forecasting hours to days ahead. Given the importance of synoptic and mesoscale variability for various aspects of renewable energy generation, numerical weather prediction and coupled climate models will grow in importance for India's energy sector.

Climate services also play an important role in the development of infrastructure resilience. With the ever-increasing complexity and growing uncertainty in intensity, duration, and magnitudes of threats (both natural and man-made), there is a need for early integration of resilience into the design of a system of systems that shape the societies we live in. In the Indian context, there is an urgent need to bring resilience research to the mainstream, establish methods for seamless data sharing among infrastructure managers, and incentivize the best practices within and across systems that foster the resilience of the critical Infrastructure lifelines of the nation. Climate information can be used to develop and modify existing design codes, tracking of health and risks of critical infrastructure, development of best practice codes for climate-ready solutions.

I. AGRICULTURE

V Geetalakshmi

Introduction and background

Agriculture sector involves many stakeholders who require climate services at different level. A recent assessment of the global state of climate services by the World Meteorological Organization (WMO) shows that 85% of countries identified climate services as a crucial component for agricultural and food security in planning and decision-making. Climate services are essential for making informed decisions and planning long-term adaptation to climate change expenditures. Climate services are also recognized as a key enabling instrument for scaling climate-smart agriculture, integrating necessary adaptation, and capturing potential mitigation of climate change and variability (Lipper et al. 2014).

The climate has a broad effect on agriculture, including farm-level production, processing, transportation, and storage, as well as marketing (WMO, 2019). Several reports have emphasized that India is at risk of frequent drought, flood, water stress and erosion etc. In such a scenario, there is an urgent need for appropriate adaptation and mitigation strategies to address climate change threats to the agriculture sector. Consequently, several initiatives aimed at enhancing stakeholders' access to tailored and contextual climate information for adapting farming practices to climate and socioeconomic risks are being promoted (Vaughan and Dessai, 2014). In this regard, Climate Services (CS) has become a popular initiative.

Climate services for agriculture provide appropriate climate information, impact-based forecasts on crops, livestock, forestry, and fisheries to manage climate risks, and weather-informed agricultural advisories to mitigate extreme weather, leading to social, environmental, and economic benefits (Brasseur and Gallardo, 2016). Climate information and associated services have demonstrably led to improved agricultural and food security outcomes and benefits for stakeholders in the sector around the globe. The capacities to deliver and access these services are highly uneven across regions and countries (WMO, 2019). Lack of national capacity for last-mile communication, lack of user-driven and participatory tailoring of services, insufficient translation of relevant services into actionable products, and the strong digital divide across and within countries are the main barriers to the effective and equitable uptake of climate services. The ways to overcome these barriers and challenges (Fig 9.1) across the entire climate services value chain, from production to delivery of the services include i.) Enhancing knowledge and capacity building, ii) Improving information products, iii) Creating effective and efficient information delivery and use, and iv) Ensuring institutional and policy support.

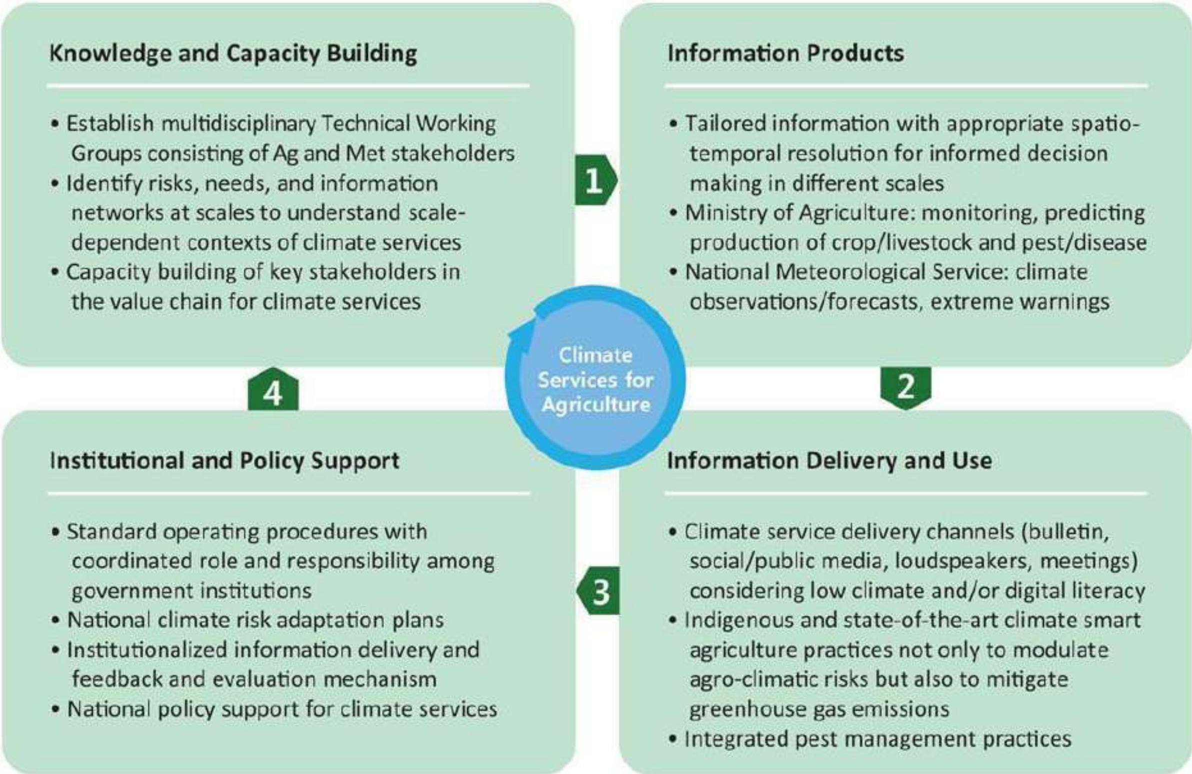


Figure 9.1. Key components of climate services framework for agriculture (AMS, 2023).

Developing effective climate services for agricultural users is an interdisciplinary process that involves many steps and actors (Fig 9.2). The general process should be tailored to the local context and to the needs and preferences of the intended users. Another major challenge is the communication and uptake of climate-informed advisories and early warnings. A series of feedback mechanisms should systematically integrate the producers and users of information in the co-design and co-production of climate services.

Figure 9.2: Fundamental steps for reaching the last mile in the climate services framework (FAO, 2020)

Key Objectives

- Strengthening of access to and uptake of relevant Demand-led weather and climate information
- Investing in supply-side capital and capacities of climate service providers
- Developing demand-led climate services and addressing last mile barrier through multi-stakeholder governance
- Translating existing research and climate service products into practice through partnerships
- Monitoring and evaluation of socioeconomic benefits associated with climate services

ROADMAP

Short term

i. Observations and datasets

a) **Access to multiple data Sources**: The scientific community needs to use adequate data to understand climate risks and address climate change challenges. Despite the technological advances, access to multiple sources of data such as observed, gauge-based gridded data, reanalysis and satellite climate data products are relatively limited. Efforts should be taken to better connect the digital technology, computer science, and data science communities with the climate change science, policy and practitioner communities. The digital data collection technologies, such as satellite remote sensing and low-cost sensors provide new advances in data collection, which can be used to address existing data gaps.

b) **Improved observations and data sharing**: The lack of observational data significantly limits the quality of information used by governments and all stakeholders as the basis for important decisions such as those related to the climate services value chain supporting agricultural production. Local observations are important for local purposes, but they are also the basis of global climate forecasts and projections. Installation of Automatic Weather Stations (AWS) to record weather parameters will improve the coverage of quality data relevant to agro-weather services. Continuous access to observations at high resolution could improve the forecasting skills of climate models and generate robust agro-advisories. There are many Automatic Weather Stations (AWS) installed by state and central Government agencies under various climate action initiatives, but inaccessible for a collective purpose. All-weather observations from manual observatories and the larger and denser AWS network can be linked to a single/common repository and made available in support of improving numerical weather prediction and climate analysis and translating them into quality climate services. There should be a standard for AWS sensors procured by Government agencies in order to ensure the quality of the data observed in the AWS and sensors must pass the qua ty check before installation, which is to be mandatory.

c) **Institutional arrangement for data sharing**: Systematic observations are the basis for crucial climate action and sustainable agriculture. Reliable and real-time observational weather data is the fundamental source for forecasting weather with good accuracy and effective climate action in an area. Agricultural and meteorological data can be shared in a common database to increase the accessibility to dataset. Creation of working groups of national entities including ministries and research institutions will help establish data-sharing and co-production outputs.

ii. Climate modelling and forecasting

India Meteorological Department (IMD, New Delhi), in collaboration with Indian Institute of Tropical Meteorology (IIM, Pune) is continuously taking steps to improve the accuracy of the weather forecast. Currently, India Meteorological Department is giving both district and block level (12km) Medium-Range Weather Forecast (MRWF) to all SAUs for agricultural purposes. As weather forecasts become progressively more accurate and timelier, high-resolution weather forecasting systems will be highly useful for farmers to tackle climate risks. IMD can take initiative to give medium-range weather forecast information on a village scale (<3km) to increase the use of forecasts in farm decision-making. The resolution and frequency of Seasonal Climate Forecast (SCF) may be improved to provide SCF at the district level with monthly rainfall instead of giving a whole season of rainfall at the regional scale. Updating the SCF every month with three months lead time would increase the reliability of SCF. The Extended Range Forecast (ERFS) can be operationalized with higher spatial resolution and frequent updates. All types of forecasts need to be validated with the observed values in order to improve the forecast accuracy.

It is important to give focus on developing the weather forecast and climate change projection at high resolution and also addressing the uncertainty issues in the projection of climate. Regional climate projections can be used to inform national and local impact assessments and adaptation plans. The Ministry of Earth Science (MoES) can assist each state to produce downscaled climate projections. It can set up a Regional Climate cell to impart training to scientists from SAUs on dynamic downscaling of CMIP climate projections to local scales or provide the dynamically downscaled outputs to each SAUs as part of various climate change projects. The MoES can place a climate modeling scientist/ Big data analyst at each SAUs which has an agro-meteorology division to train the post-graduate students/research scholars on climate modelling/ climate analysis using big data and expand the application of climate science and modeling in agriculture.

iii. **Climate data for end users**

The main issues with climate data from the end user's perceptive are **accessibility and reliability**. There are ways that the government and private sector can collaborate and respond to the climate data problem such as i) **Translation**: climate data must be made understandable to the average person, which can be done by people and/or technology, ii) **Collaboration**: There is an opportunity for the public and private sectors and academia to work together in new and innovative ways to ensure climate data meet the needs of end-users, iii) **Guidance**: Experts need to guide climate data end users on choices such as where to find and use reliable data, and also understanding its limitations.

Last mile stakeholders in agriculture sector include farmers, farmers clubs, farmer associations, cooperatives and fisher folk. They need location specific weekly, sub-seasonal and seasonal temperature and rainfall outlook and expected long term changes in rainfall and temperature. To take farming decisions such as selection of cultivars, decision on planting dates, irrigation practices, time and quantum of application of fertilizer and pest management, it is necessary to provide bi-weekly/weekly agro-advisories on key crops, livestock and fisheries. Information about likeliness, timing and potential impacts of severe weather events such as wet and dry (drought) spells, temperature extremes and cyclone warning to manage the crop production risk are also necessary. Potential impacts of short- to medium-term climate change on crops/ livestock/ fisheries/ management practices are important for making decisions on investment decisions.

Sub-national (district / state) level stakeholders includes officials of Department of Agriculture, Agrometeorological field units, Agricultural universities, farmers training centres, emergency planners, extension services and NGOs. They need seamless forecasts on rainfall, temperature, wind speed and cloud cover for making sub-national policy and planning including risk management and budgeting, reservoir planning, ground water management and for planning input purchase and supply.

National level stakeholders include Ministries of Agriculture, Food Security and Rural Development, Fertilizer industry and crop Insurance companies. Information required by them are monsoon status, departure of monsoon rainfall from normal conditions, seamless forecast information, coastal flood warnings, early warning of extreme events such cyclones, drought and flood and heat waves for and likely social & economic impacts would help in issuing timely warnings to relevant public and private sector players. Climate information is used for making national policy and development plans including vulnerability mapping, risk assessment/ management, investment planning, estimating agricultural productivity for planning export and import of commodities and for development of weather-based crop insurance products.

iv. **Digital innovation for the development and dissemination of climate service information**

Climate information can be effectively utilized by integrating it into the development of data-driven dynamic advisory service, which has been evolving rapidly in recent years and is a cost-effective way to improve farmers' ability to deal with weather-related risks in crop production. The incorporation of technological advancements such as machine learning or AI, and modelling approaches could strengthen agro-met advisory services.

Real-time data received from the weather stations and satellites are to be processed and analysed right away to create actionable alerts and recommendations or advisories in a way that can be easily applied by end-users. Ex. Agro-climate data can be used to forecast pest and disease outbreak for early response and management. Actions based on timely and accurate information can be preventive rather than reactive.

Dissemination to end-users includes, alerts and advice for farmers are shared through bulletins, radio messages, SMS, smartphone application, social media and web platform. Providing customized voice messages to each farmer may effectively help them in climate-informed decision-making.

Long term

a) The development or improvement of climate models must be in accordance with the strategy for weather forecasting. In this context, it is desirable to develop a single integrated model system over a variety of temporal (nowcasting to centennial) and spatial (convective scale to climate system Earth modelling) scales.
b) Earth System modeling has enormous potential, but it also requires significant advances in high-performance computing, cloud computing, machine learning and artificial intelligence and as well as increased satellite observations and private sector involvement. Enhanced

collaborations between Member States, WMO, academia, and industry are required for a step change in such advancements.

c) Governments can increase public investments in weather observing systems and supercomputing facilities to improve forecast accuracy.
d) Governments need to create a suitable mechanism to encourage Private Partnership Engagement (PPE) for the effective use of technological developments and innovation that provides a new opportunity for climate services to reach end users.
e) The government needs to put a lot more effort into coordinating and promoting R&D consortia with international cooperation at the State level.
f) Government needs to accelerate public investments in climate services to reach the last mile –marginal and small farming communities and communicate actionable information in an equitable and effective manner to end users, ensuring that no one is left behind.
g) Climate information and products are to be developed and delivered at the farm level for managing risks in agriculture effectively and sustaining crop productivity.

REFERENCES

American Meteorological Society (AMS) Bulletin. (2023). 104, 2; 10.1175/BAMS-D-22-0123.1

Brasseur, G. P., & L. Gallard. (2016).Climate services: Lessons learned and future prospects. Earth's Future, 4, 79–89, https://doi.org/10.1002/2015EF000338.

FAO. (2020). https://www.fao.org/climate-change/our-work/areas-of-work/climate-risk-management/climateservices/en/

Lipper, L., & Coauthors, (2014): Climate-smart agriculture for food security. Nature Climate Change, 4, 1068–1072, https://doi.org/10.1038/nclimate2437.

Vaughan, C., & Dessai, S. (2014).Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. WIREs Clim. Chang. 5, 587–603.

WMO, 2019: 2019 state of climate services: Agriculture and food security. WMO Rep. 1242, 44 pp.

II. WATER

Manish K Goyal

Water: A Global Context

Background

Water is the most abundant and ubiquitous resource on earth, but most of the water is not accessible for human consumption and crop production because it is either salty or locked in the ice caps (Saleth & Dinar, 2004). Only around 0.26 % of the global freshwater reserve is physically accessible to us to meet our domestic, agricultural, and industrial requirements (Saleth & Dinar, 2004). Our global hydrological cycle and the earth's climate are intricately linked,with alterations in climate variability having the potential to impact the availability of water resources.. Climate change and anthropogenic activities have altered the course of water resources, reshaping their distribution and availability. as depicted in Figures 9.3 and 9.4 (Abbott et al., 2019; Pltonykova et al., 2020).

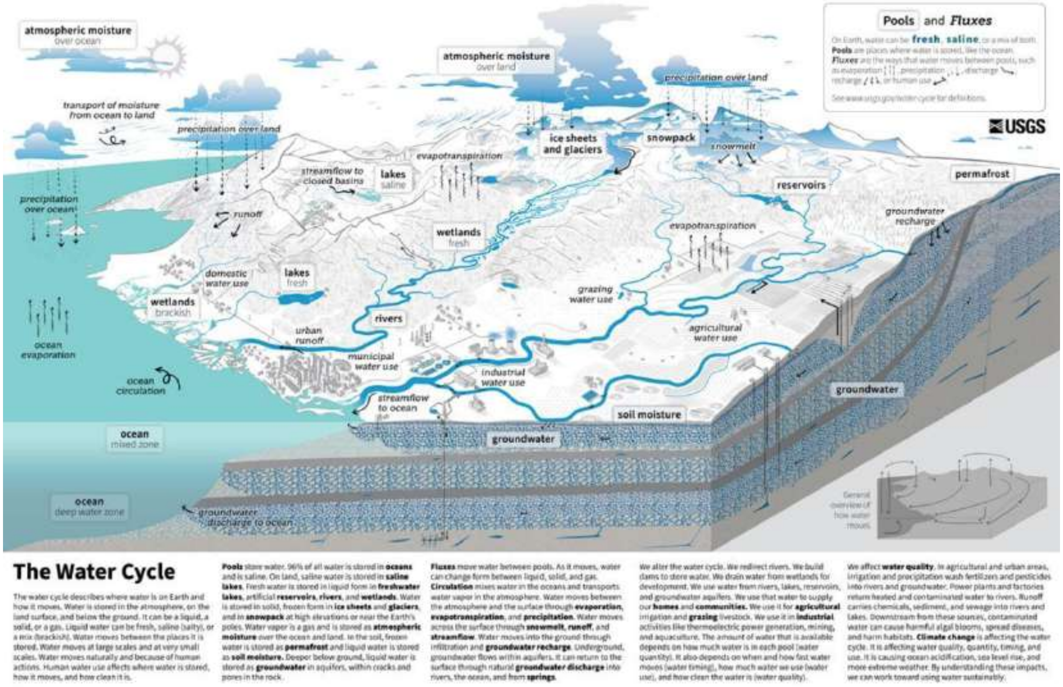


Figure 9.3: The Water Cycle (USGS, 2022)

Water demands can be categorized into three major categories, i.e., agriculture, industry, and domestic requirements, which account for 69%, 19%, and 12%, respectively, at the global scale (FAO, 2016). Global water use has been increasing by 10% per decade since the 1980s (FAO, 2016), led by population growth, consumerism, and socio-economic development. Primarily, this rise in water use is guided by increasing demands in developing countries, predominantly as a function of growing industrialization and improvement in water-sanitation services (Burek et al., 2016; IEA, 2016; Kitamori et al., 2012). Agriculture sector accounts for the highest water consumption, and it is projected that food requirements will increase by 60 % by 2050, leading to a potential rise in water requirements (FAO, 2017).

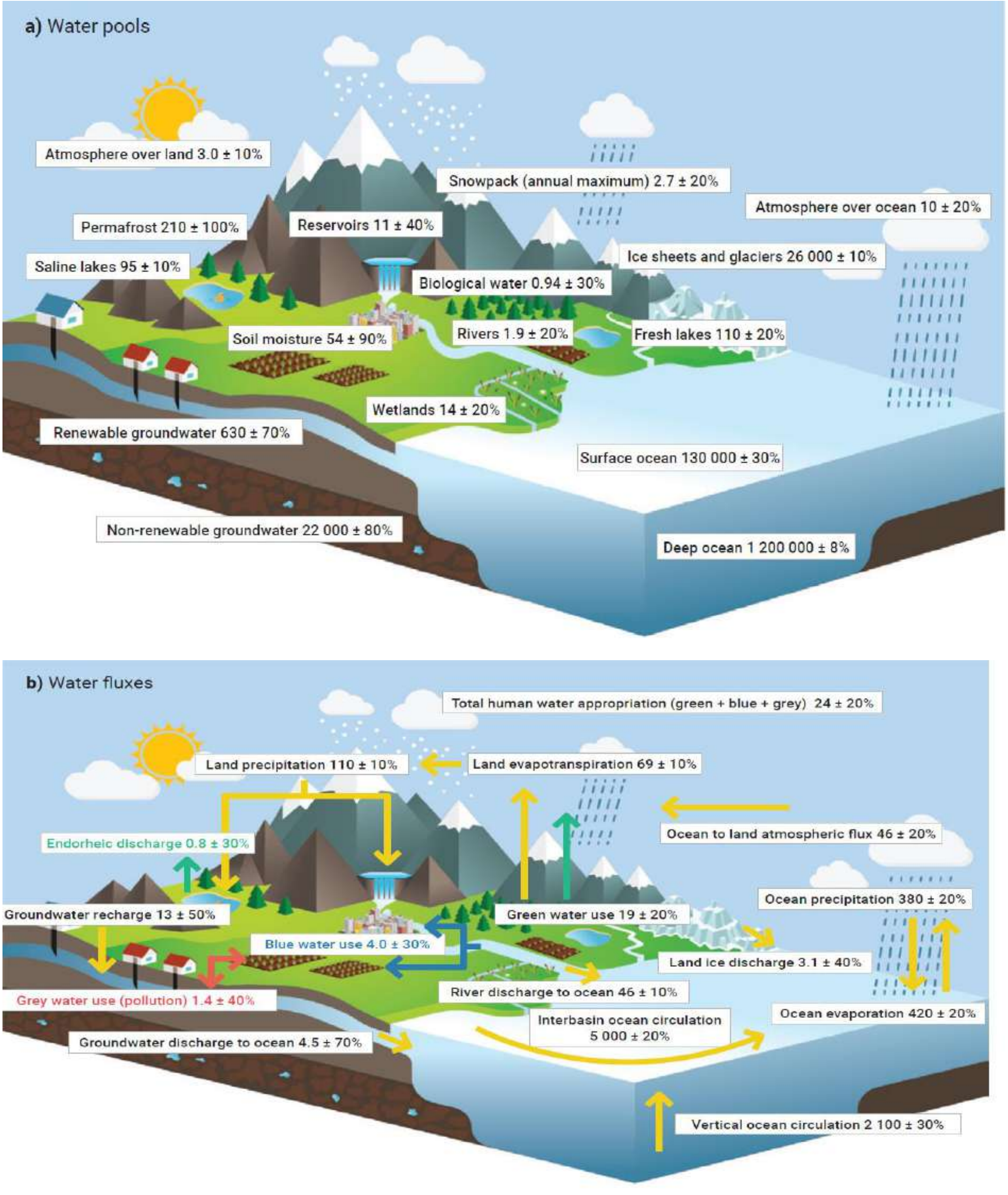


Figure 9.4. Hydrological Cycle a) Major water pools (expressed in 10^3 km^3) (a) and water fluxes (expressed in 10^3 km^3 yr^{-1}) (b). Uncertainty represents the range of recent estimates expressed in %. In b, total human water use (~$24*10^3$ km^3 yr^{-1}) is separated into green (soil moisture used by human crops and rangelands, green arrow); blue (consumptive water use by agriculture, industry, and domestic activity, blue arrow); and grey (water necessary to dilute human pollutants, which is represented with pink shading, red arrow) (Source: (Abbott et al., 2019; Pltonykova et al., 2020))

These projected demands can be met sustainably, with increasing water use efficiency in the agricultural sector and a paradigm shift towards consumption of low water-demanding diets. Also, improving water use-efficiency in industrial and domestic sectors can play a vital role, especially in developed countries, where per capita domestic water uses, and the portion of industrial usage is relatively high compared to developing or emerging economies.

Climate change influences a substantial portion of the population by causing them to reside in areas where the average rainfall significantly deviates from the norms established in the 20th century. It is estimated that about half a billion population live in adverse wet conditions, mainly in mid to high latitudes. While more than 160 million population live in adverse drier conditions, mainly in the tropics and sub-tropical regions. In addition, with variability in mean precipitation, precipitation patterns and river flows change with time.

The surge in river flows is prominently observed in high latitudes, while declining flows are observed in mid- and low latitudes. Therefore, we observe a noticeable increase in the socio-economic impacts across wetter and drier world regions (IPCC, 2022).

From the perspective of water stress, which is defined as water use for available water supply. More than 2 billion people face water stress, of which 22 countries experience severe water stress (UN, 2018). Additionally, around 4 billion people face water scarcity for at least one month per year (Mekonnen & Hoekstra, 2016). Also, more than 1.6 billion people face economic water scarcity, i.e., water is physically available, and scarcity is due to insufficient infrastructure to collect, transport, and treat water for human consumption (Molden, 2013). The levels of physical water stress are likely to increase, with a rise in water demands due to increasing population and intensification of the hydrological cycle due to climate change (UN, 2018). With changing climate, dry/wet regions will tend to become drier/wetter, thereby exacerbating water stress in regions where it has not been a recurring phenomenon.

Globally, water quality problems are pervasive in developed and developing countries (UN, 2018). Around 80% of industrial and municipal wastewater is directly released into the environment without treatment, leading to deleterious effects on human health and ecosystems. This portion is much higher in developing and under-developed countries due to a lack of wastewater treatment and sanitation facilities (Connor et al., 2017). Nutrient loadings remain one of the most prevalent forms of water pollution, and most nutrient emissions originate from agriculture. Its management is considered as one of the most prevalent global water quality-related challenges (OECD, 2017). Clean water availability and its management for the rapidly increasing global population are challenging tasks for all countries worldwide. According to the United Nations, more than 733 million people live worldwide in high to critical water stress regions. Over the course of the last 300 years, the world has witnessed a loss of 85% of its wetlands. In the present scenario, it is estimated that there will be 1.6 billion people worldwide by 2030 who lack safely managed water. Thus, it requires four times increase in the efforts to conserve water resources and develop its associated infrastructure (United Nations, 2022). Due to this, on March 2021, United Nations member states conducted a high-level meeting to implement the water-associated goals and targets per the 2030 agenda of Sustainable Development Goals (SDGs). The key outcome of the meeting is that achieving the SDG 6 targets by 2030 will require the mobilization of 1.7 trillion US Dollars, i.e., three times higher than the present level of investment for water-associated infrastructure. It will require collaborations between governments, private and public-spirited organizations, and extensive use of new innovative technologies (United Nations, 2021a). In the Indian context, related to SDG 6, assessing the previous effort's outcomes and future water supply sources is essential (Figure 9.5).

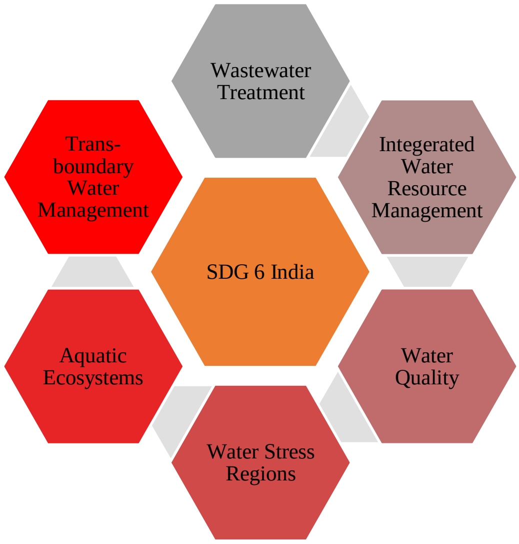


Figure 9.5: Water Parameters for achieving SDG 6 Targets by 2030

It is estimated that 22% of river basins in India are observing rapid changes in the area covered by surface waters. Several studies reported that 15% of Himalayan glaciers in India were lost. India's efficiency in domestic wastewater treatment is markedly low, at just 27%, which affects surface and sub-surface water quality. India received 305 million US Dollars in 2020 for water and sanitation-related development assistance. The water management efficiency needs significant improvement in India as it has 18% of the world's population, with 4% of the mean world's annual runoff in the streams. India has more than 600 million public who rely on agriculture, and approximately 2/3rd of the agricultural land under cultivation is dependent entirely on precipitation and sub-surface water resources. Electricity subsidies to farmers in India led to more exploitation of groundwater resources than the United States and China combined. It is determined that India has a 0.3 metre average annual drawdown in the water table and 4 metre in certain regions. Regions in India that are under significant water stress, often coincide with areas where crops that require a high amount of water, such as sugarcane, paddy, and various grains, are cultivated. Water consumption is generally categorized as virtual and real water. Real water consumption is when we consume water directly, while virtual water consumption is through agriculture and industrial products. India is mainly the net exporter of virtual water, like Canada, Russia, Argentina, etc. China which has a higher population and economy than India, has 28% less water consumption annually than India (NITI Aayog, 2022). Therefore, it is imperative for India to take significant steps in water management practices through Irrigation, integrated water management systems, research, and Innovation of new water-saving techniques.

There are inextricable linkages between water, climate, and significant socio-economic sectors, i.e., ecosystems, human settlements, energy, agriculture and sanitation, and hygiene. Therefore, given the increased scarcity and variability caused by climate change, “water management will be crucial in determining whether the world achieves the Sustainable Development Goals.”

Key Objectives

The key objectives are as follows:

- **Development of Continuous monitoring tools for freshwater ecosystems and their water availability for local and national population**

The water supply and demand issues need to be resolved to achieve the targets of SDG 6, 2030, and it will require an assessment of several factors. These include observing the changes in the spatial extent of water ecosystems over time, identifying the actions for protecting freshwater ecosystems, restoring degraded freshwater ecosystems, and increasing the monitoring and uptake of water datasets. Satellite and ground-based validated datasets with higher correlation efficiency for monitoring the surface water (Permanent, Seasonal, and Reservoir), water quality (turbidity and trophic state), and wetlands (Inland and Mangroves) need to be used for continuous monitoring. Drinking water quality and water availability at each home should be considered on a prior basis. The river basin's vulnerability to climate change and anthropogenic activities assessment is required to determine the vulnerable population in its surroundings (United Nations, 2021b).

There are different sources of water pollution, i.e., domestic sewer, domestic non-sewer, Urban surface runoff, Industry, Agriculture, and sediment pollution (UNEP, 2016). Myriad technical options exist for pollution prevention, treatment of wastewater, safe reuse of wastewater, protection, and restoration of ecosystems. A strict review of technical options for water quality is the need of the hour. Furthermore, water quality protection can be done through finance and governance to protect and restore freshwaters.

- **Prepare action plans to protect freshwater water-associated ecosystems, including glaciers, mountains, wetlands, rivers, aquifers, lakes, etc., against climate change and human activities**

Water quality improvement strategies through diminishing pollution, complete stoppage of the release of hazardous chemicals, eradicating disposal and release of hazardous substances, minimize the disposal of untreated wastewater with increasing the reusing and recycling capacity worldwide. Initiate the water bodies rejuvenation and transboundary water management cooperation at regional, national, and international levels (Wankhade, 2017).

The intricate interplay between climate and water, particularly in the context of greenhouse gas (GHG) emissions, often lacks sufficient acknowledgment, resulting in its exclusion from various mitigation strategies. The countries' actions aren't required for water-related GHG emissions except for wastewater. The knowledge gap of interactions between water cycles, freshwater availability, freshwater limitations, and mitigation of GHG emissions water leads to freshwater being an underestimated factor in climate change mitigation. To fulfil this gap, there is a dire requirement for a comprehensive assessment of freshwater's role in climate mitigation.

- **Future supply and demand patterns of regional water sources, including both permanent and seasonal sources of supply**

By 2030, minimize the water scarcity or stress regions through the assessment of the future increase in population, urbanization, migration due to climate change, and industrialization. To safeguard future generations from the potential risks of water-related disasters, it is crucial that we employ various methods to thoroughly evaluate future patterns of water demand and supply. (Wankhade, 2017).

ROADMAP

Roadmaps are planning methods involving short-term goals to long-term goals. It helps the administrations to initiate technical and functional innovations to meet a combined challenge.

Short-term (by 2030)

It is crucial to assess the future water demands from industry, agriculture, and domestic sectors with certainty. New, improved, novel assessment methodologies should be developed to reduce uncertainties in future projections and draft better management strategies. Regarding water quality management, a strict review of technical and management options should be reviewed. Pollution prevention is achieved in various ways, i.e., by increasing water use efficiency in households, manufacturing, and industries (introduction of water-efficient production processes, water recycling, and wastewater reuse) and agriculture (water-efficient irrigation and tailwater return systems) (UNEP, 2016). And through the reduction of waste produced and urban green infrastructures.

Further, wastewater treatment through mechanical/primary treatment, biological/secondary treatment, chemical/tertiary treatment, and advanced treatment. Furthermore, different technical options for the safe reuse of wastewater, i.e., the Use of stormwater and the Reuse of domestic wastewater and sludge, should be reviewed. Moreover, investments on governance in the water and sanitation sector should be increased. In the context of climate-smart water resource management, the availability of present and future freshwater and its impacts (positive or negative) is to be accounted for in climate mitigation planning and action. Further, the mitigation plan should also account for significant emission reduction potential from water and sanitation management. Also, nature-based solutions (NBS) can be game changers, delivering multiple benefits for people and the environment. The NBS should be prioritized based on the following measures: improve soil and water productivity, safeguard freshwater resources, sequester carbon, and ensure sustainable and resilient livelihoods.

The future roadmap for achieving the clean water and sanitation SDGs by 2030 will initially require a baseline assessment of water resources and associated infrastructure datasets. Secondly, based on the above datasets, we have to initiate the science-policy dialogue and implement the actions for achieving the SDG 6 targets per 2030 SDGs at regional and national levels (Water Future, 2022). For Developing Knowledge and strategies for achieving the SDG 6 targets by 2030, we have to assess the present policies, water database, issues, and research & development (R&D) process in continuation (Figure 9.6).

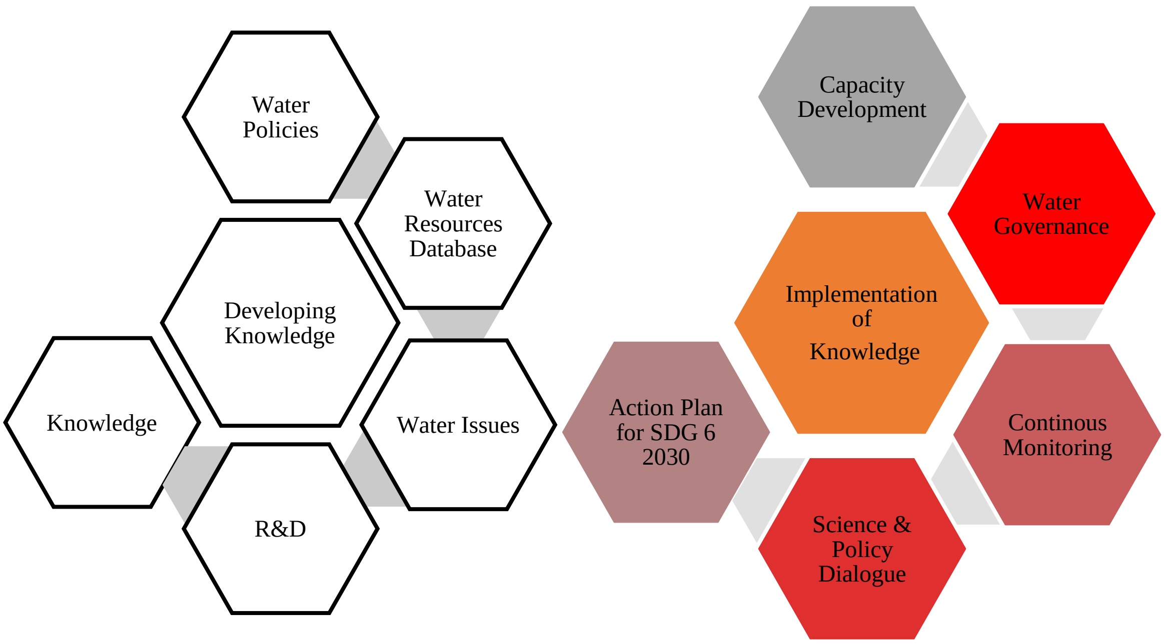


Figure 9.6: Developing and Implementing the Knowledge for SDG 6, 2030

Based on the developed Knowledge, we have to initiate the capacity development of the stakeholders, implement the modification in the water governance policies, initiate the science-policy dialogue, and continuously monitor water ecosystem quality to make the strategic action plan for SDG-6 2030. The short-term and long-term solutions have to be implemented; like in Punjab, for the short-term solution, RO Filters were installed, while for a more extended period, a canal system was made where treated water is needed. Government initiatives like "Pradhan Mantri Krishi Sinchai Yojana" and "Har Khet Ko Pani" need to be implemented. The water use efficiency needs to be increased by 20%, stringent equitable water distribution regulations, incentivization to farmers for water conservation, improvement in recycling and reuse of the treated water, etc. Command area development and water management in agriculture through repair, renovation, and rejuvenation of water bodies are fewer approaches to getting more crops per drop of water (NITI Aayog, 2022).

The 2030 plan should aim to provide India-specific modeling through the integration of land surface models by including glacier components, Indian region-specific water management, and crop practices, and through coupling groundwater with lateral flows. It will require establishing a high-resolution soil moisture monitoring network and merging terrestrial water data with satellite measurements, as shown in Fig 9.7. The policy associated with water governance should be built on multi-levels and polycentric to provide actions from multiple stakeholders at different scales with higher chances for learning prospects among all the associated persons. The concept of polycentrism in policy-making enables the absence of a single center of power. Thus, it will legitimately provide the decision through multiple decision makers in ensuring a fair decision-making process with the inclusion of marginalized, young, and indigenous peoples. The utility of evidence-based methods improves polycentric water governance by providing information for supporting regional and multi-level decisions making. In this manner, a water governance policy with a polycentric approach benefits water users through enhanced communication, consent, inclusiveness, and beneficial outputs for all.

An efficient polycentric process requires proper information sharing, coordination, and effective participation from all stakeholders (IPCC, 2022).

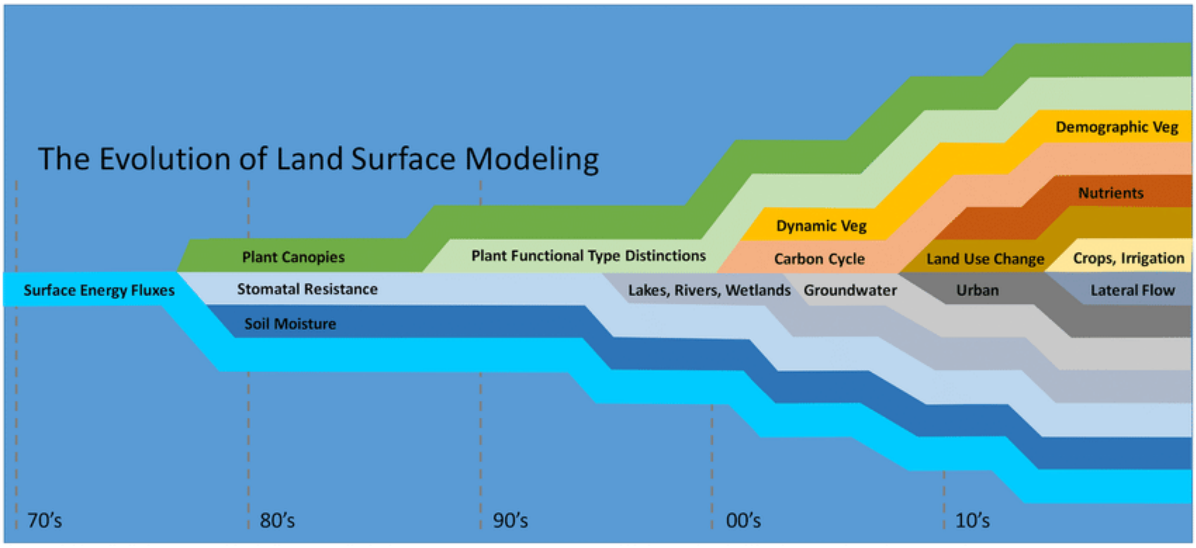


Figure 9.7: A schematic depiction of the evolution of land surface model process representation through time, representing the approximate timing of the emergence of different model components as commonly employed features of Earth system models. Note that all modeling groups follow a different pathway and that this diagram is primarily intended to illustrate increasing complexity through time (Fisher & Koven, 2020).

Therefore, through policy modifications and scientific assessment of current water issues observed by local and national populations, we must prepare a strategic action plan for SDG 6 2030 through government and stakeholders' involvement for equitable access to quality and affordable water for the desired purpose.

Long-term (Beyond 2030)

A long-term roadmap for achieving clean water and sanitation SDGs in India would involve a multi-faceted, sustained approach that addresses the issues of infrastructure, policy, education, and technology (NITI Aayog, 2022).

Infrastructure Development: Significant investments should be made in developing and upgrading water and sanitation facilities, especially in rural and underserved areas. This includes creating new facilities, enhancing existing ones, and employing advanced water purification systems

Policy Reforms: Policy interventions are required to ensure water is used efficiently and distributed equitably. This could involve stricter enforcement of water quality standards, regulation of industrial waste, and promotion of water conservation

Public Education: Large-scale education and awareness programs can enhance public understanding of the importance of water sanitation and hygiene practices

Innovation: Long-term efforts should also focus on investing in innovative, sustainable technologies for water purification, eco-friendly sanitation, and water-efficient practices

Achieving these goals requires a collaborative effort from government agencies, NGOs, the private sector, and local communities. Long-term strategies might include:

Investment in Sustainable Technologies: Over the long term, investing in sustainable water and sanitation technologies, such as decentralized wastewater treatment systems, can provide scalable solutions

Capacity Building: Training local communities in water and sanitation management can ensure the sustainability of initiatives. This involves education and skill-building at the grassroots level

Water Conservation Strategies: Implementing water conservation strategies like rainwater harvesting and groundwater recharge can help ensure water security in the face of climate change and increasing demand

Achieving the clean water and sanitation SDGs in India is a complex task that requires coordinated efforts from various stakeholders, including government agencies, NGOs, the private sector, and local communities. However, with a comprehensive, long-term roadmap in place, it is an achievable goal.

REFERENCES

Abbott, B. W., Bishop, K., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., et al. (2019). Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, *12*(7), 533–540. https://doi.org/10.1038/s41561-019-0374-y

Burek, P., Satoh, Y., Fischer, G., Kahil, M. T., Scherzer, A., Tramberend, S., et al. (2016). Water futures and solution-fast track initiative.

Connor, R., Renata, A., Ortigara, C., Koncagül, E., Uhlenbrook, S., Lamizana-Diallo, B. M., et al. (2017). The united nations world water development report 2017. wastewater: the untapped resource. *The United Nations World Water Development Report*.

FAO. (2016). AQUASTAT website. Food and Agriculture Organization of the United Nations (FAO). *Website Accessed on [2016/05/07]*.

FAO. (2017). *Water for Sustainable Food and Agriculture*. Rome.

Fisher, R. A., & Koven, C. D. (2020). Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems. *Journal of Advances in Modeling Earth Systems*, *12*(4). https://doi.org/10.1029/2018MS001453

IEA. (2016). *Water Energy Nexus: Excerpt from the World Energy Outlook 2016*. Paris.

IPCC. (2022). *IPCC_AR6_WGII_FinalDraft_FullReport*. *IPCC*. Retrieved from https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

Kitamori, K., Manders, T., Dellink, R., & Tabeau, A. A. (2012). *OECD environmental outlook to 2050: the consequences of inaction*. OECD.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*(2), e1500323.

Molden, D. (2013). *Water for food water for life: A comprehensive assessment of water management in agriculture*. Routledge.

NITI Aayog. (2022). *SDG 6: Ensure Availability and Sustainable Management of Water and Sanitation for all*. Retrieved from https://www.niti.gov.in/writereaddata/files/Report_SDG-6_v1.pdf

OECD. (2017). *Diffuse Pollution, Degraded Waters: Emerging Policy Solutions*. IWA Publishing.

Pltonykova, H., Koeppel, S., Bernardini, F., Tiefenauer-Linardon, S., & de Strasser, L. (2020). The United Nations World Water Development Report 2020: Water and Climate Change.

Saleth, R. M., & Dinar, A. (2004). *The institutional economics of water: a cross-country analysis of institutions and performance*. World Bank Publications.

UN. (2018). *Sustainable Development Goal 6: Synthesis Report 2018 on Water and Sanitation*. New York.

UNEP, A. (2016). A snapshot of the world's water quality: towards a global assessment. *Nairobi, United Nations Environment Programme*.

United Nations. (2021a). *Progress on Freshwater Ecosystems*. Retrieved from https://www.unwater.org/sites/default/files/app/uploads/2021/09/SDG6_Indicator_Report_661_Progress-on-Water-related-Ecosystems_2021_EN.pdf

United Nations. (2021b). *Progress on Freshwater Ecosystems*.

United Nations. (2022). About UN-Water. Retrieved from https://www.unwater.org/about-un-water

USGS. (2022). The Water Cycle. Retrieved December 6, 2022, from https://www.usgs.gov/media/images/water-cycle-png

Wankhade, K. (2017). *Operationalising SDG 6 in Urban India*. Retrieved from https://iihs.co.in/knowledge-gateway/wp-content/uploads/2017/10/Operationalising-SDG-6.pdf

Water Future. (2022). Water Future. Retrieved from https://water-future.org/

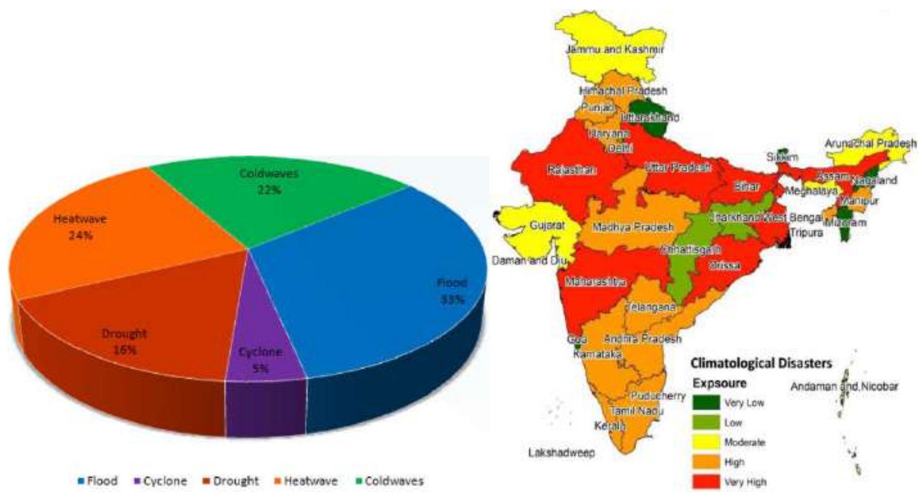
III. DISASTER RISK MITIGATION

Subhankar Karmakar & Anil Kumar Gupta

Hydro-climatic Extremes and Disasters

Extreme hydro-climatic events lead to disastrous impacts on human societies and ecosystems. Anthropogenic climate change has intensely distressed the hydrological cycle. Climate change has caused an increase in the frequency of hydro-climatic extremes, such as floods, droughts, and heatwaves, along with an increase in extreme magnitudes over the past several decades in many parts of the world. Though the Covid-19 pandemic has been the most significant concern globally since the past three years, the threat of disasters like cyclones, floods, droughts, forest fires and tsunamis is looming overhead. Necessary measures are the need of the hour to manage the disasters even if they cannot be prevented. According to the Centre for Research on the Epidemiology of Disasters (CRED), from 2000 to 2019, nearly 104,614 people lost their life due to flood-related disasters alone, and approximately 1.65 billion people were affected globally. In the year 2021 alone, global economic losses due to disasters estimated to $280 billion. A holistic approach for disaster risk mitigation and management to minimize losses and development resilience is, therefore, needs to be drawn and implemented at all levels and across the geographies.

Due to its unique geo-climatic and socio-economic conditions, India is vulnerable to floods, droughts, cyclones, tsunamis, earthquakes, urban flooding, landslides, avalanches, and forest fire. Figure 9.8a shows occurrence of five climatic events during 1995-2020. According to the 2020-2021 Annual Report of National Disaster Management Authority (NDMA), 27 out of 36 States and Union Territories (UTs) in the country are disaster-prone. 58.6% landmass is prone to earthquakes of moderate to very high intensity; 12% of the land is prone to flood and river erosion; out of 7,516 km of coastline, 5,700 km is prone to cyclones and tsunamis; 68% of the cultivable land is vulnerable to drought, hilly areas are at risk from landslides and avalanches, and over 15% of the landmass is prone to landslides. A total of 5,161 Urban Local Bodies (ULBs) are prone to urban flooding.



(a) (b)

Figure 9.8. (a) Occurrence by disaster type (number of events occurred) - Five climate related disaster events; (b) A composite climatic disaster frequency map over the period 1995-2020 [Gupta et al. (2021), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH India]

Figure 9.8b shows a recent state-level composite spatial analysis showed that eight out of 36 states in India have experienced more than 50 disasters during 1995-2020. The highest number of climatic events is recorded in Rajasthan (n=72), followed by Odisha (n=67), Uttar Pradesh (n=66), West Bengal (n=66), Bihar (n=64), Maharashtra (n=60), Andhra Pradesh (n=52). Fire incidents, industrial accidents, and other human-induced disasters involving chemical, biological and radioactive materials are additional hazards which have underscored the need for strengthening mitigation, preparedness, and response measures. In most of the densely populated cities in India, population heterogeneity is too large to allow reliable coarse scale vulnerability assessment. Globally and in India too, almost over 70% of disasters are related with climate or water systems. A foremost need of disaster management is to assess disaster risks and vulnerability of different social groups or economic sectors, at a local level. Disaster risk mitigation and preparedness would prove to be more cost effective and efficient when established at local level to achieve a community-wide goal.

Key Objectives

1. To make disaster risk management and resilience efforts truly multidisciplinary in nature, considering the roles of science & technology, social science and humanities, policy-planning and governance, general public, and ground actions.
2. To pursue an integrated approach of policy planning and decision making along with improvement of disaster forecasting and preparedness.
3. To provide adequate social and environmental adaptative support through education and identifying optimal combination of structural/non-structural measures.

Roadmap Short-term (by 2030)

- Establishment of public database on hydro-climatic parameters for research community backed with effective network of surface observations stations.
- Devising a simulation-optimization based protocol for establishing multipurpose shelters.
- Improved near-real-time forecasting for engineered reservoir operation and early warning dissemination
- All geographies and all sectors of development to have adequate risk and vulnerability assessment in place with disaster risk management strategies.
- Integrating adaptation to climate change including ecosystem-based adaptation, infrastructure resilience, local institutions and capacities to be among core agenda.
- Utilizing the above referred knowledge base from S&T based interventions, lessons from past disasters, pilot interventions and innovations, and enable effective risk reduction and resilience strategies along with ground execution.
- Disaster management is established as a discipline of knowledge and practice, across environmental & climate science, social & humanities, management, engineering, law & governance, etc.

Long-Term (Beyond 2030)

- Disaster knowledge/information management, urban planning and governance through practicing balkanization and pluralization – Proper coordination among apex planning authorities through joint data collection, inventorization and implementation lead to efficient management. The water governance and flood disaster management in cities are mostly handled by multiple authorities that lead to balkanization and pluralization. To address these issues, a multidisciplinary and multi-stakeholder approach with a holistic perspective is critical.

- Nature based solution – for example, strengthening and establishing mangrove plantations covering relevant flood affected coastal areas, which will be a part of integrated coastal zone management.
- Infrastructure, industry and cities – their risks and vulnerabilities in the changing development and climate extremes, to be seen a prime concern for disaster risk reduction and resilience.
- Rebuilding social capital – engaging youth and children, and all the sections of society towards integrated resilience building and a culture of safety and disaster preparedness.
- All the cities, villages and organizations/intuitions and establishments to comprehensive disaster risk reduction and resilience strategies, and capacities.
- Revamping and improving disaster risk reduction strategies to address changing risk scenarios and developmental settings including disruptive changes in S&T and societal settings.
- Promoting sustainability integration into adaptation, resilience and disaster risk reduction mechanisms, for example, mainstreaming green growth and circular economy principles, greening disaster response and post-disaster recovery, etc.

Summary

Climate-related disasters have both increased and intensified owing to climatic change. The structural measures of disaster mitigation involve adaptive structural design, while the non-structural measures include improving forecasting, human capacities, policy-planning and promoting stakeholder-centric solutions. Climate models usually perform well except for extremes which is a major bottleneck in this direction. Improving extreme simulations and forecasts, using innovative solutions to make them stakeholder-centric, and designing climate adaptation strategies ought to be considered as high priority research areas. Furthermore, multiple hazards (simultaneous or sequential extremes) degrade the resilience of natural and human infrastructural systems as well as weaken emergency response systems at the local to national level, thus leading to 'loss amplification'. A risk-based approach is particularly needed when a disaster is inherently compound/multivariate in nature. IPCC conceptualizes Risk as a product of hazard, vulnerability, response and exposure. Generating sector-specific risk maps pertaining to extremes are of immense importance. The sensitivity of risk to different vulnerability indicators provides adaptation strategies for improving critical indicators and reducing the risk. Engineering designs connecting risk to resilience should be a major research area yet awaiting the significant attention it deserves. It also calls for changes in design guidelines, incorporation of climate information in technological development, and planning for quick recovery mechanisms for sustainable disaster mitigation.

IV. INFRASTRUCTURE RESILIENCE

Udit Bhatia

Introduction and Background

Sustainable Development Goal 9, as delineated by the United Nations Foundation, puts the emphasis on constructing "Resilient Infrastructure, promoting sustainable Industrialization, and fostering innovation" (UN Foundation). This goal has particular pertinence to the Asian regions, including India, where despite the meteoric pace of economic growth and development, the critical infrastructure is still lacking. The infrastructure deficit is so pronounced that it necessitates an additional investment of approximately $434 billion each year to meet the demands of the region.

This presents a significant challenge but also a remarkable opportunity, especially with the 2030 goal of inclusive and sustainable industrialization on the horizon. India has the potential to take the lead in this endeavor, focusing on developing high-quality, reliable, and resilient infrastructure. The philosophy behind this should be not just to build it right the first time but also to proactively retrofit the existing infrastructure rather than merely repairing it reactively when it fails.

India is particularly vulnerable to many natural threats that could severely impact its critical infrastructure systems. These threats include intensifying weather extremes, technological failures, or a combination of both, which are likely to become more frequent and severe in both the near and long-term future due to global changes (Ganguly et al., 2018).

Recognizing these threats, many nations around the world have prioritized enhancing the resilience of their infrastructure. In this context, infrastructure resilience refers to "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (Ganguly et al., 2018). This requires proactive and coordinated efforts to maintain secure, functioning, and resilient critical infrastructure.

However, the task of enhancing infrastructure resilience becomes particularly challenging given the evolving nature of threats, the increasing intensity and frequency of hydrometeorological events (extreme events with extremely low probabilities of occurrence), and the increasing complexity of infrastructure systems (Linkov et al., 2014). Two key reasons for this are the rapid advances in digital technology and the widespread use of the Internet of Things (IoTs), which have made these systems more interconnected and complex than ever before.

Moreover, the uncertainties associated with the vulnerabilities of these complex systems, along with the lack of reliable estimates of the statistics of climatic extremes, complicate our ability to design and protect critical infrastructure against these threats. Hence, traditional risk-based approaches that focus on strengthening individual components to withstand identical threats to an acceptable level and prevent overall system failure may no longer be sufficient. Therefore, new, innovative approaches are needed to ensure the resilience of critical infrastructure in the face of these rapidly evolving threats.

However, before resilience is translated from a mere buzzword to an operational paradigm, the following deeply rooted and mutually reinforcing barriers should be addressed in the Indian context:

1. **Non-recognition of physical infrastructure systems and their complex multiplex as *Lifelines* and *Critical Infrastructure Systems*:** The Information Technology Act of 2000 defines Critical Information Infrastructure as *"a computer resource, the incapacitation or destruction of which shall have a debilitating impact on national security, economy, public health or safety,"* there is need of more comprehensive legal and engineering framework to recognize the physical infrastructure systems as ***lifeline systems*** (including water and waste-water networks, multimodal transportation systems, communication, power distribution networks, and healthcare systems), and other allied infrastructures (e.g., industries, waste-management systems, finance, and banking) as Critical Infrastructure systems with clear understanding that any perturbation to functioning of these systems, physical or virtual, so critical to India that their sub-optimal functionality would have spiralling and debilitating impact on security, national security, confidence of investors, and national public health.
2. **Lack of pre-identified recovery intervention strategies:** We lack a comprehensive theoretical framework and multistakeholder data-sharing mechanisms for real-time tracking of systems' functionality before, during, and after the hazards. Hence, we are unable to identify the most effective interventions and design principles to improve and fortify our most critical systems. There is a need to go beyond frugal innovations to systematic engineering frameworks to have pre-defined restoration strategies ready for these complex systems.
3. **Increasing and untamed complexity of both isolated and interdependent systems:** In the last seven years, India has added an impressive 1,41,000 Kms to their highway network and 900 trains to the railways' network, has moved swiftly and indigenously to 5G technologies, and optical fiber systems in communication systems, has achieved the goal of near 100% electrification in rural, semi-urban and urban areas. However, these developments come with the unresolved puzzle of complexity. A failure in one of these perceived isolated systems can percolate through the network multiplex, given the strong coupling between *power distribution systems* and *communication*, *communication* and *transportation systems*, *transportation systems* and *communication systems*, and so on (***Figure 9.9***).
4. **Lack of theoretical frameworks to quantify the resilience of interdependent systems:** For critical infrastructure systems, we lack a comprehensive functional map of the constituents of Critical Infrastructure (CI), let alone their interdependence. All too often, this knowledge comes only after a disaster exposes vulnerable components and critically disrupts the flow of goods, services, and information. In the context of evolving hazards (including the intensification of hydrometeorological extremes in warming scenarios), integrating the dynamics of interdependent infrastructure systems with the hyper-resolution hazard models becomes even more critical.
5. **Limited confidence in the understanding of spatiotemporal evolution of extremes at resolutions that matter the most:** Long-term observation records (both in-situ and remotely sensed) and Projections from General Circulation Models (or GCMs) are typically available at resolutions ranging from a few kilometers to hundreds of kilometers. While there has been significant progress in translating these coarse-resolution outputs to fine-resolution outputs (Harilal et al., 2021), the upper limit of such downscaling exercises is limited by the resolution and quality of observations available and also inherits the uncertainties from GCMs through the boundary conditions(Pielke Sr. & Wilby, 2012). Moreover, the infrastructure operators, and managers, would want actionable information at the facility level, which operates at scales ranging from sub-meter to a few meters. Hence, identifying the most credible

resolution from stressors (hydrometeorological extremes including floods, heatwaves, extreme precipitation-induced landslides) and stressed system side remains an unsolved puzzle.

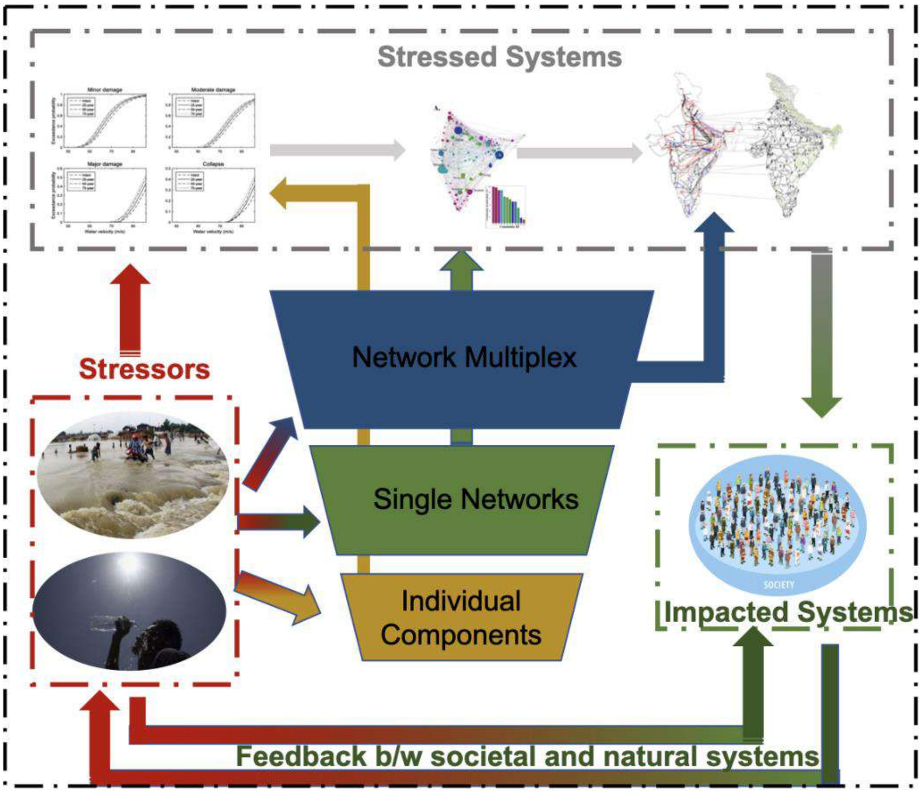


Figure 9.9: Network of Networks: Complex web of direct and indirect feedback between stressors (including climate and weather extremes such as floods, heatwaves, and droughts), stressed systems (including individual components of infrastructure systems and their multiplex), and impacted systems (societies) [Adapted from (Bhatia & Ganguly, 2016)]

Roadmap for Resilient Infrastructure

The challenges to be addressed to turn the challenge of complexity into opportunity are manifolds ranging from improved understanding of threat-infrastructure interaction to uncertainty informed cost-benefit analysis while being accountable for intangible consequences for humans and societal systems. While aging critical Infrastructure systems in developed economies are receiving grades of C and D ("ASCE's 2021 American Infrastructure Report Card | GPA," 2017), India should learn from the experiences as we continue to strengthen and build on the multiplex of these infrastructure systems. The roadmap to enable these developments should address the following near-time (**by 2030**) and beyond (**2030-2050**) challenges:

- Updating the existing design codes and legislative procedures that keep system thinking at the forefront while continuing to include the most updated component-level design provisions. The updated engineering design provisions will help break the engineering and policy stagnation that nations (both developing and developed) are struggling with in the backdrop of evolving extremes (both natural and man-made). Moreover, strengthening the legal framework and enforcement of the same would ensure the increased trust of national and international investors in the Nation's trade ecosystem ***(Near Term)***.

- Investment in Research & Development infrastructure to enable technologies that keep real-time track of the "health" of Critical Infrastructure Systems and their dependence on multiple spatiotemporal resolutions: While India has shown remarkable growth in integrating automation systems (including Supervisory Control and Data Acquisition (SCADA) for maintaining railways and multi-reservoir operations), the data integration across the Industries and Institutions is not seamless. While new modeling and simulation techniques that quantify the resilience of highly complex systems are being developed, their validation for real-world engineered infrastructure systems remains the challenge. India has the opportunity to be at the forefront of bridging this gap by investing in research and translation capabilities and using its startup ecosystems for intellectual investment in critical Infrastructure resilience **(Near term to Long term)**.
- The existing practices of design and maintenance of Infrastructure systems need to incentivize the best practices at the micro- (facility management) and macro-levels that foster the "climate-ready" solutions for resilient infrastructures. This can be achieved by legislative and regulatory means **(Long term)**.

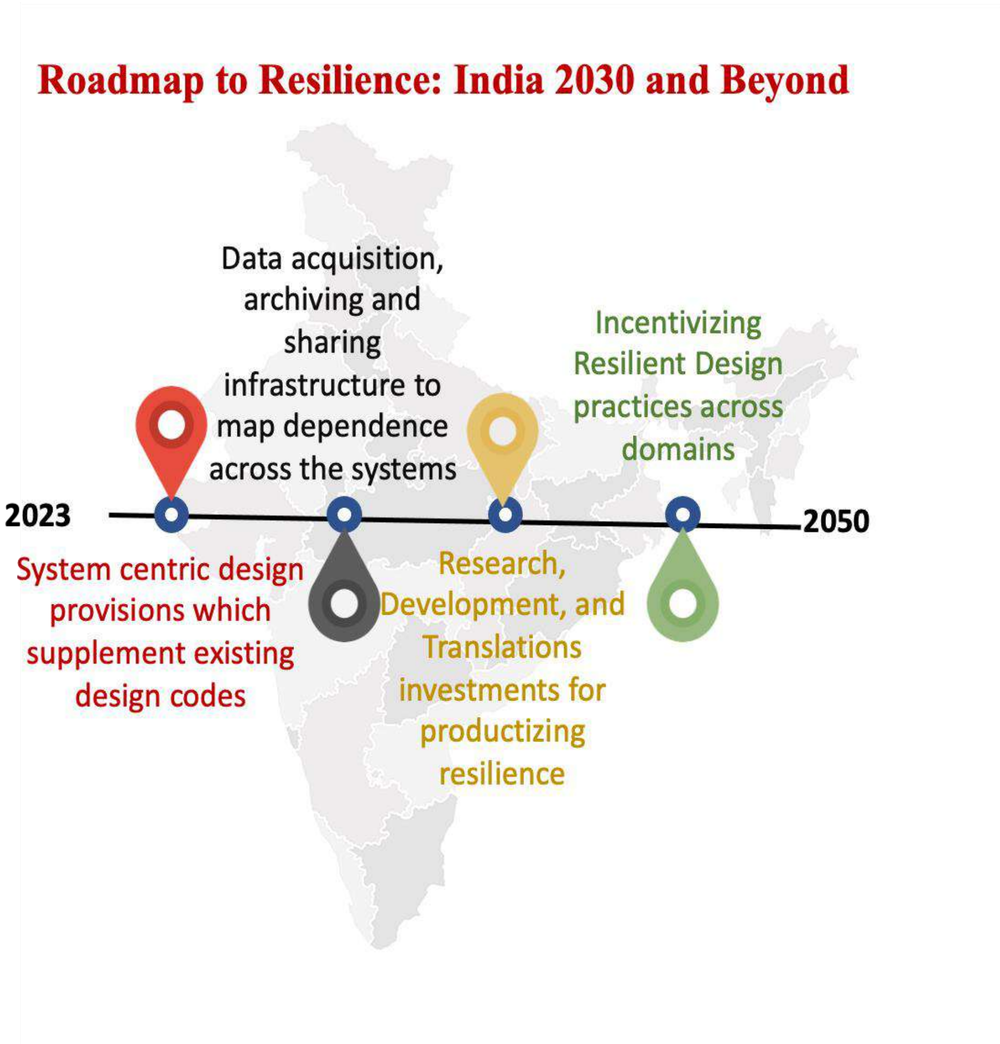


Figure 9.10: Overarching summary of the resilience roadmap

Summary

With the ever-increasing complexity and growing uncertainty in intensity, duration, and magnitudes of threats (both natural and man-made) (Dave, 2021), there is a need for early integration of resilience into the design of a system of systems that shape societies we live in. In the Indian context, there is an urgent need to bring resilience research to the mainstream, establish methods for seamless data sharing among infrastructure managers, and incentivize the best practices within and across systems that foster the resilience of the critical Infrastructure lifelines of the nation. Globally, the research and tools that enable the quantification of resilience are progressing (Bhatia et al., 2015; Gao et al., 2016). However, there remain challenges and opportunities to translate resilience from a technical jargon to an operational paradigm for the greater good of society in the immediate future and beyond.

REFERENCES

ASCE's 2021 American Infrastructure Report Card | GPA: C-. (2017, January 11). Retrieved November 14, 2022, from https://infrastructurereportcard.org/

Bhatia, U., & Ganguly, A. R. (2016). Network Science Perspectives on Engineering Adaptation to Climate Change and Weather Extremes. In *Large-Scale Machine Learning in the Earth Sciences*. Chapman and Hall/CRC.

Bhatia, U., Kumar, D., Kodra, E., & Ganguly, A. R. (2015). Network Science Based Quantification of Resilience Demonstrated on the Indian Railways Network. *PLOS ONE*, *10*(11), e0141890. https://doi.org/10.1371/journal.pone.0141890

Dave, R. and S. S., Srikrishnan and Bhatia, Udit. (2021). Extreme precipitation induced concurrent events trigger prolonged disruptions in regional road networks. *Environmental Research Letters*. Retrieved from http://iopscience.iop.org/article/10.1088/1748-9326/ac2d67

Ganguly, A. R., Bhatia, U., Flynn, S. E., Bhatia, U., & Flynn, S. E. (2018). *Critical Infrastructures Resilience : Policy and Engineering Principles*. Routledge. https://doi.org/10.4324/9781315153049

Gao, J., Barzel, B., & Barabási, A.-L. (2016). Universal resilience patterns in complex networks. *Nature*, *530*(7590), 307–312. https://doi.org/10.1038/nature16948

Harilal, N., Singh, M., & Bhatia, U. (2021). Augmented convolutional LSTMs for generation of high-resolution climate change projections. *IEEE Access*, *9*, 25208–25218.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., et al. (2014). Changing the resilience paradigm. *Nature Climate Change*, *4*, 407–409. https://doi.org/10.1038/nclimate2227

Pielke Sr., R. A., & Wilby, R. L. (2012). Regional climate downscaling: What's the point? *Eos, Transactions American Geophysical Union*, *93*(5), 52–53. https://doi.org/10.1029/2012EO050008

V. HEALTH

Sagnik Dey

Climate Services for the Health Sector in India

Introduction and Background

Evidence of climate change impacts on human health is unequivocal globally (Costello et al., 2009). According to the World Health Organization (WHO), nearly 23% of global deaths in 2012 were attributable to factors affected by climate variability (Neira and Pruss-Ustun, 2016). Changes in extreme weather events and gradual changes in weather and climatic conditions directly and indirectly (through environmental and ecological changes) impact physical and mental health (Gulzar et al., 2021). Adverse impacts on public health due to climate change have been identified to be a major hindrance to meeting multiple sustainable development goals.

India, home to 1.4 billion population, is highly vulnerable to climate change. Deaths due to extreme weather events have been on the rise in India in the last five decades (Ray et al., 2021). Heatwaves in India have been increasing (Pai et al., 2013; Rohini et al., 2016), leading to health burdens, including mortality (Azhar et al., 2014; Mazdiyasni et al., 2017). Heatwaves and associated burdens are projected to increase manifold in the future under global warming (Mishra et al., 2017; Murari et al., 2015). Air pollution exposure in India is one of the highest in India (Balakrishnan et al., 2019). The health burden attributable to air pollution has been found to be high (Pandey et al., 2021) and is expected to increase in the future, more under the RCP8.5 scenario than under the RCP4.5 scenario (Chowdhury et al., 2018). Mitigating air pollution can potentially influence heat stress (Dey et al., 2021). Air pollution also influences the regional climate (Ganguly et al., 2012). Patterns of vector-borne and infectious diseases are shifting under climate change due to changes in the transmission window (Sarkar et al., 2019; Dhara et al., 2013; Dhiman et al., 2010). For developing nations like India, the healthcare sector needs to be prepared for climate adaptation and resilience to reduce the public health burden. However, a consolidated and sustained effort is required to continue scientific research and translate the knowledge to strengthen the healthcare system.

There have been several efforts in the recent past to promote interdisciplinary research on climate change and human health. The first country-level dialogue on this topic started in 2009 in a joint Indo-US workshop on climate change and human health (Bush et al., 2010). As a follow-up on the initial discussion, the Department of Science and Technology (DST) coordinated a network program on 'climate change and health' under the national mission on strategic knowledge for climate change (NMSKCC) to facilitate collaborative research between climate and health scientists (Dash et al., 2016). In the first phase, three thematic areas – 'vector-borne diseases,' 'air pollution,' and 'heat stress' were identified. In the second phase, 'water-borne diseases' and 'tribal health' were added as two additional thematic areas. The network program enabled generating key strategic knowledge in this area and demonstrated the added benefit of such interdisciplinary work (Dash et al., 2016). The National Centre for Disease Control (NCDC) initiated a national program on 'climate change and human health' with objectives of creating awareness among healthcare sectors and general populations, strengthening the preparedness of the healthcare sector to reduce the health burden of climate change and foster interdisciplinary research to fill the knowledge gap.

The India Meteorological Department (IMD) is mandated to provide climate services for sectoral applications. The general climate products are not always directly useful for sector-specific applications, primarily due to the mismatch in spatial and temporal scales of the products and the lack of expertise in effectively using the product for the health sector. The growing concern about the impacts of climate change on health posed an urgent need to develop climate services focused specifically on the health sector in India.

Current knowledge gaps

While research on climate change impacts on health has been continuing in India, the efforts are still disjointed and often do not cater to the actual need of the healthcare system. Based on an exhaustive literature review, the following major knowledge gaps are identified.

Lack of a systematic approach to translating knowledge into action. The first step to building the resilience of the health system to climate change is to identify and map indicators of climate adaptation. While the past and ongoing research have been generating a lot of information, a general lack of systematic approach is hindering translating the knowledge into action (Manyuchi et al., 2021). The climate model outputs cannot be directly utilized for health sector applications due to the mismatch in the available and desired scale. The climate products must be useable and context-relevant (Vollstedt et al., 2021) for vulnerability assessment. Climate services should facilitate policymakers to adopt a reactive adaptation approach in a resource-constrained setting or incremental adaptation for proactive interventions. The services should also be useful for the health workers and population to respond effectively to crisis, sustain normal functions during the crisis, and reorganize if the need arises (Kruk et al., 2015). A framework representative of the Indian scenario needs to be defined and evolved for a holistic and systematic approach to translate knowledge into action through tailor-made climate products for the health sector.

Lack of adequate expertise to carry out translational research. Another big challenge is the lack of adequate expertise to handle and process climate data for healthcare applications. India does not have a critical mass of public health experts to deal with the climate change impacts and effectively manage the six building blocks (WHO, 2007) – service delivery, health workforce, information system, access to essential medicines, health and climate financing, and governance. Health experts lack basic training in climate data analytics and management, leading to difficulty in carrying out translational research. Strengthening collaboration between health and climate scientists will surely enhance the fundamental and technical skills required to resolve interdisciplinary problems, but the broad ecosystem in the Indian curriculum is lacking. The new education policy emphasizes this critical gap, and country-wide adoption of the policy is expected to promote interdisciplinary research in a synergistic way.

Lack of indigenous health-risk assessment. In India, climate change and health research have been mostly focused on air pollution, heat stress, and infectious diseases. Beyond these three sub-domains, where knowledge has significantly improved due to the current efforts, many areas remained untouched. A recent Lancet Commission report (Swiburn et al., 2019) has highlighted that climate change, malnutrition, and obesity co-occur in space and time, leading to a global syndemic. Malnutrition is the leading health risk in India (Dandona et al., 2017); however, focused research on the impact of climate change on malnutrition is lacking. The impact of climate change on mental health is emerging as a new but important topic (Hwong et al., 2022). For India, it is highly important (Padhy et al., 2015) as the mental health burden is already high (Sagar et al., 2020). The third area where a significant knowledge gap exists is disentangling the environmental and social determinants through which climate change impacts health outcomes via complex pathways.

Even in the domains where studies are undergoing, health-risk assessment heavily relies on studies conducted in developed countries. The representativeness of the exposure-response functions from global studies needs to be evaluated for the Indian population through a systematic approach. Indigenous cohort studies need to be planned and executed for target populations with priority for vulnerable groups.

Lack of a consolidated data management system. A robust data management system is critical in providing climate services for the health sector. However, such a system does not exist in India. Data management system extends beyond routine data collection and forecasting efforts currently in place through various agencies and covers appropriate data quality control strategies, harmonize data across scales, and analytical tools to make sense of the data and build a data architecture so that the data can be integrated with models and be accessed seamlessly across a wide range of users (Gani et al., 2022). This calls for institutional capacity building in data management and informatics.

ROADMAP

Short-term (for 2030)

Customized (downscaled) climate products for applications in the health sector. The scales of traditional climate products are coarser for local applications. For health applications, climate data should be customized and downscaled and then aggregated at the level at which health data are available. Climate data comes with uncertainty. A key challenge to climate services is effectively identifying and conveying the methodological differences and limitations in climate data and the impact they may have on the decision-making process (Fletcher et al., 2021). The other challenge is the effective choice of the climate product given various climate change and socioeconomic pathways scenarios for the future. Climate services should identify, process, and disseminate the most appropriate and robust data (based on sensitivity analysis) to the health sector through mutual discussion. The dissemination strategy needs to be defined carefully based on the potential applications.

Strengthen disease management system. The development of the climate-resilient health infrastructure requires merging the climate and health information systems. Two aspects are equally important. The health systems should be prepared to function normally even if a climate crisis strikes. Second, the health system should recognize the ‘tipping points’ and prepare itself to withstand climatic risks in the future and protect public health (Lotz-Sistika et al., 2016). A foremost requirement for this is a robust disease surveillance system. Climate services should leverage this surveillance system and develop a disease forecasting system to enable and empower the health sector to make early decisions and minimize the health burden. India can learn from global experiences (e.g., McGough et al., 2021; Zinszer et al., 2012). The existing healthcare workers should be provided with specialized training to prepare them to handle climate-related risks. The basic requirement is developing suitable indicators to map the climate change impacts on the health sector at a local scale.

Develop indigenous exposure-response functions. Exposure-response functions are critical to assess the vulnerability of environmental exposure affected by climate change. For most of the health outcomes, the exposure-response functions are developed based on cohorts in developed countries. It is critical to deriving indigenous exposure-response functions to address the major limitations in the current approach to disease burden assessment. For the estimation of the health burden attributable to air pollution, the key assumption of uniform toxicity across a wide range of particulate matter levels may not be relevant across the globe, as already indicated by recent studies. It is not realistically possible for India to ever meet the counterfactual exposure as the natural background dust is higher than the WHO air quality guideline (Pai et al., 2022). The global heat indices may not be adequate in capturing the physiological stress across the climate zones of India (Dey et al., 2021). India-specific heat index needs to be developed and used in heat action plans. For many disease outcomes, there is not a single indigenous study. Existing secondary health data can be useful in carrying out time-series, cross-sectional or case-control studies to generate evidence in quick time before long-term cohorts can be carefully planned and executed. This also requires basic epidemiological training for a broader community.

Create analytical tools for climate data applications in the health sector. Augmented observational systems and improved computational facilities have enabled the generation of a large volume of different types of data that vary in space and time scales. It is extremely important to develop a comprehensive and seamless data architecture to ensure good science and bridge gaps between science and policy. The data need to be harmonized and quality controlled before dissemination, but most importantly, the data structure required for the researchers and policymakers is different. Therefore, analytical tools need to be developed to cater to the specific needs. Data management is a specialized field, and institutional capacity needs to be developed to manage data information systems in a more centralized way for easy access and better services.

Develop a decision support system. The development of a decision support system should enable effective policymaking. Three aspects are critical here. First, the decision support system should provide early warning for the disease outcomes that are linked to weather and climate extremes and are affected by climate variability. This should be carried out at sub-seasonal to seasonal time scales and utilize the routine weather forecasting integrated with the disease surveillance system. The system should establish a seamless data management architecture for easy exchange of information between all relevant stakeholders. Second, the decision support system should allow policymakers to examine the potential impacts of environmental exposure modulated by weather and climate events on various health outcomes under different scenarios. Third, the system should integrate (indigenous) exposure-response functions for various health outcomes to estimate potential health benefits of target reduction in exposure following the adaptation and mitigation efforts in the future.

Long-term (Beyond 2030)

Make curriculum inclusive of an interdisciplinary approach. Including climate change as a core topic in the medical curriculum will make health professionals aware of the impending challenges from an early stage of their career and help address the lack of expertise in managing climate data in the health sector. Health professionals should be prepared (with specialized training) for community engagement and outreach activities on the health risks of climate change. Similarly, climate scientists should be taught about potential sectoral applications of climate data and the sector-specific requirements.

Create an ecosystem for interdisciplinary research. Fostering collaboration between health and climate scientists through student and faculty exchange, joint academic programs, and projects are the way forward to promote interdisciplinary research in India. Interdisciplinary research does not always get desired approval from institutions and funding agencies. A mechanism needs to be created to sustain interdisciplinary activities across the institutions. New courses, specialized training programs, and new academic programs are some of the key initiatives that institutions can consider. The MoU between IIT-Delhi (leading technical institute) and AIIMS Delhi (leading medical institute) is an example that showed the right way to promote interdisciplinary research, under which various academic activities are currently being undertaken.

A systematic plan for cohorts. Cohort studies are the way forward to understanding the causal pathway between exposure and health outcomes. Cohorts require a long-term commitment from the funding agencies to sustain data collection and follow-ups. The past and ongoing cohorts, focusing on public health issues, can be leveraged in a retrospective manner to study climate change impacts. New cohorts should also be planned to focus on outcomes that are often neglected and on those which are more complex.

WAY FORWARD

Figure 9.11 summarizes the way forward to develop a robust climate service for the health sector. It requires integration and harmonization of information flowing in from four key components – weather forecasting, climate projection, health surveillance and surveys, and epidemiological research. The weather forecast at a shorter time scale needs to be translated into a disease early warning system for target populations based on region-specific health risks derived from epidemiological research based on health and exposure data. Institutional capacity needs to be parallelly developed to act upon such warnings and minimize the threats to health from extreme events and other climate-related impacts. These experiences, coupled with the current understanding of the health risk, should lead to the development of adaptation strategies based on the assessment of vulnerability to climate change at a local scale for the future. The health data collected through surveillance and surveys will play a pivotal role in tracking the efficacy of local interventions in protecting human health. The existing tools need to be revamped and redesigned to cater to these requirements for local scale use. Modern tools like machine learning and artificial intelligence can be explored to support data processing and management. The most critical aspect would be having a cogent and open data policy to facilitate the seamless use of climate and health data for research and services.

India has already invested in network programs on climate change and human health through the Department of Science and Technology and the National Center for Disease Control. These programs brought the climate and health scientists closer and have generated important scientific knowledge. The way forward is to take a major leap and accelerate the progress by synergizing the core components that are presented in this chapter. This will enable the policymakers to evaluate and plan to allocate human capital and infrastructural resources based on the actual requirements.

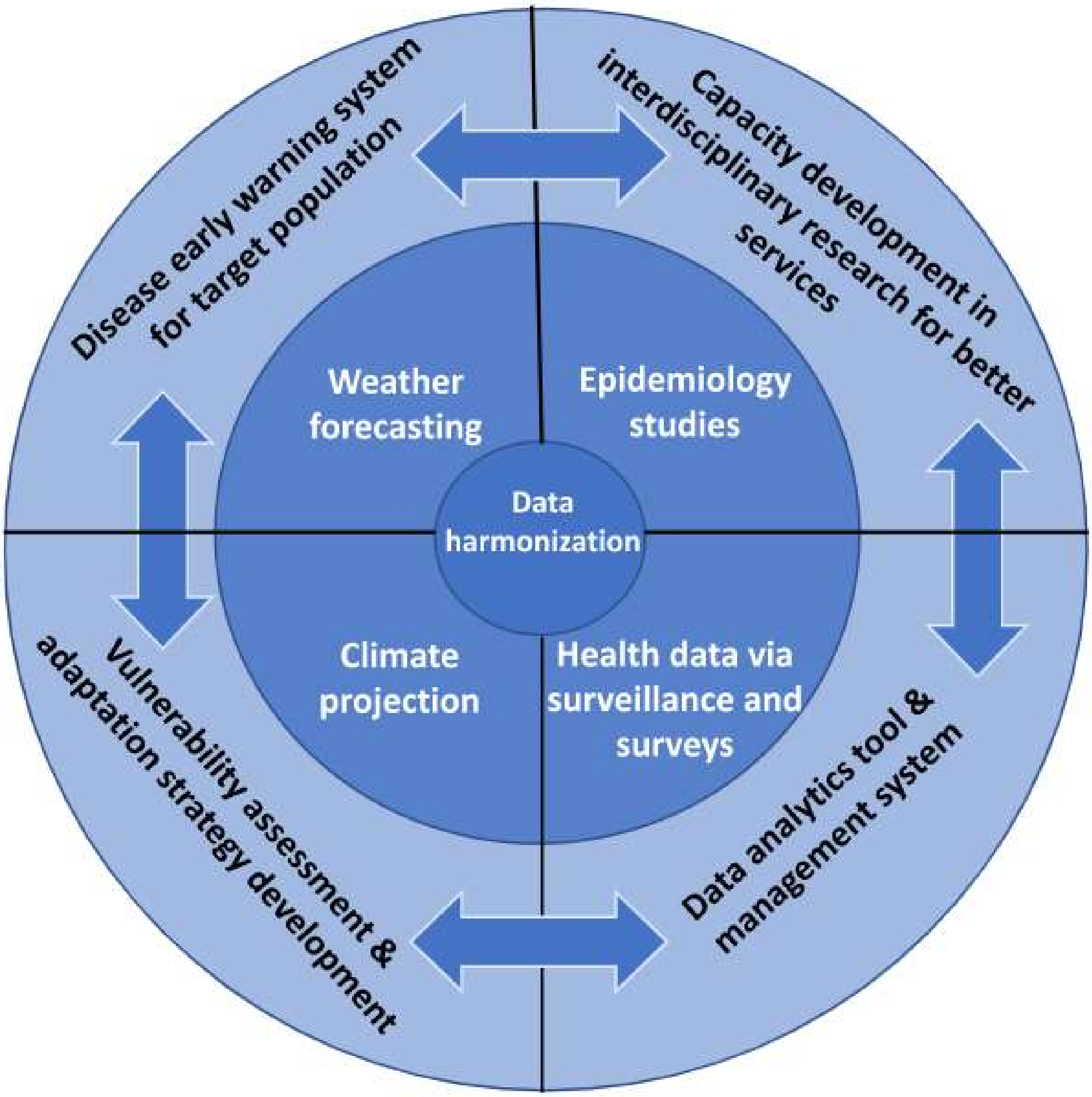


Figure 9.11. The framework for developing climate-resilient health infrastructure for India.

REFERENCES

Azhar, G., S. Saha, P. Ganguly, D. Mavalankar and J. Madrigabo (2017), Heat wave vulnerability mapping for India, Int. J. Environ. Res Pub. Health, 14(4).

Bush, K. et al. (2010), The impact of climate change on public health in India: Future research directions, ISEE 22nd Annual Conference, Seoul, Korea.

Dandona, L. et al. (2017), Nations within a nation: variations in epidemiological transition across the states of India, 1990-2016 in the Global Burden of Disease Study, Lancet, 390, 2437-2460.

Dash, S. K., A. Gupta, and N. Mendiratta (2016), Climate change and human health, A report of the DST's national knowledge network programme on climate change and human health.

Dhara, V. R., P. J. Schramm, and G. Luber (2013), Climate change and infectious diseases in India: Implications for health care providers, Indi. J. Med. Res., 138(6), 847-852.

Dhiman, R. C., S. Pahwa, G. P. S. Dhillon, and A. P. Dash (2010), Climate change and threat of vector-borne diseases ion India: are we prepared? Parasitology res., 106, 763-773.

Fletcher, I. K., A. M. Stewart-Ibarra, M. Garcia-Diez, J. Shumake-Guillemot, and R. Lowe (2021), Climate services for health: From global observations to local interventions, Med., 2, 355-383.

Gani, S., P. Pant, S. Sarkar, N. Sharma, S. Dey, S. K. Guttikunda, K. M. AchutaRao, J. Nygard, and A. Sagar (2022), Systematizing the approach to air quality measurement and analysis in low ad middle income countries, Environ, Res. Lett., 17, 2, 021004.

Hwong, A. R. et al. (2022), Climate change and mental health research methods, gaps, and priorities: a scoping review, Lancet Plan. Health, 6(3), 281-291.

Kruk, M. E., M. Myers, S. T. Varpilah, and B. T. Dahn (2015), What is a resilient health system? Lessons from Ebola, Lancet, 385, 1910-1912.

Lotz-Sisitka, H. B. et al. (2016), Co-designing research on transgressive learning in times of climate change, Curr. Opin. Sustian., 20, 50-55.

Manyuchi, A. E., C. Vogel, C. Y. Wright, and B. Erasmus (2021), Systems approach to climate services for health, Climate Serv., 24, 100271.

Mazdiyasni, O. et al. (2017), Increasing probability of mortality during Indian heat waves, Sci. Adv., 3(6).

McGough, S. F., L. Clemente, J. Nathan Kutz, and M. Santillana (2021), A dynamic, ensemble learning approach to forecast dengue fever epidemic years in Brazil using weather and population susceptibility cycles, J. Royal Soc. Interface, 18, 2020106.

Mishra, V., S. Mukherjee, R. Kumar, and D. A. Stone (2017), Heatwave exposure in India in current, 1.5°C, and 2.0°C world, Environ. Res. Lett., 12, 124012.

Murari, K., S. Ghosh, A. Patwardhan, and E. Daly (2015), Intensification of future severe heat waves in India and their effect on heat stress and mortality, Reg. Environ. Change, 15, 569-579.

Pai, D. S., S. A. nair, and A. N. Ramnathan (2013), Long-term climatology and trends of heat waves over India during the recent 50 (years (1961-2010), Mausam, 64, 585-604.

Padhy, S. K., S. Sarkar, M. Panigrahi, and S. Paul (2015), Mental health effects of clumate change, Ind. J. Occup. Environ. Med., 19(1), 3-7.

Ray, K., R. K. Giri, S. S. Ray, A. P. Dimri, M. Rajeevan (2021), An assessment of long-term changes in mortalities due to extreme weather events in India: A study of 50 years' data, 1970-2019, Weather Clim. Serv., 32, 100315.

Rohini, P., M. Rajeevan, and A. K. Srivatsava (2016), On the variability and increasing trends of heat waves over India, Sci. Rep., 6, 26153.

Sagar, R. et al. (2020), The burden of mental disorders across the states if India: the Global Burden of Disease Study 1990-2017, Lancet Psychiatry, 7(2), 148-161.

Sarkar, S., V. Gangare, P. Singh, and R. C. Dhiman (2019), Shift in potential malaria transmission areas in India, using the fuzzy-based climate suitability malaria transmission model under changing climatic conditions, Int. J. Environ. Res. Pub. Health, 16(18), 3474.

Swinburn, B. A. et al. (2019), The global syndemic of obesity, undernutrition, and climate change: The Lancet COmmisssion report, Lancet, 393, 10173, 791-846.

Tewary, A, R. K. Mehajan, M. Golechha, D. Mavalankar (2021), Co-developing climate services for resilient public health system in India, Curr. Sci., 120, 10, 1578-1586.

Vollstedt, B., J. Koerth, M. Tsakiris, n. Nieskens, and A. T. Vafeidis (2021), Co-production of climate services: A story map for future coastal flooding for the city of Flensburg, Clim. Serv., 22, 100225.

WHO (2007), Everbody's business: strengthening health systems to improve health outcomes: WHO's framework for action, WHO, Geneva.

Zinszer, K., A. D. Verma, K. Charland, T. F. Brewer, J. S., Brownstein, Z. Sun, and D. L. Buckeridge (2012), A scoping review of malaria forecasting: past work and future directions, BMJ Open, 2, e001992.

VI. COAST

S A Sannasiraj

India is surrounded by three sides of water and has a long coastline with 30% of our population living along the coast and the Indian Ocean has accounted for 30% of the global oceanic heat content increase over the last two decades, while it is home to 30% of the world's coral reefs and 13% of global wild-catch fisheries. As India has set its path to transform from the 6th largest economy in the world (2.6 Trillion Dollars) into the 3rd largest (a 10 Trillion Dollar economy) by 2030. The development has been driven to channel, support, and fuel the boost of the economy of our country wherein India has a unique maritime position. Its 7517 km long coastline is home to nine coastal states and 1382 islands. The country has 12 major and 187 non-major ports, handling about 1400 million tons of cargo annually, as 95% of India's trade by volume transits by sea. India's Exclusive Economic Zone of over two million square kilometers is rich in living and non-living resources and holds significant recoverable resources of crude oil and of recoverable natural gas. The coastal economy also sustains over 4 million fishermen and other coastal communities. With these vast maritime interests, the Blue Economy in India has a vital relationship with the nation's economic growth. The blue economy has seven focused priority areas as follows:

1. National Accounting Framework for Blue Economy and Ocean Governance,
2. Coastal Marine Spatial Planning and Tourism,
3. Marine Fisheries, Aquaculture, and Fish Processing,
4. Manufacturing, Emerging Industries, Trade, Technology, Services, and Skill Development,
5. Logistics, Infrastructure, and Shipping (including transshipments),
6. Coastal and Deep-Sea Mining and Offshore Energy,
7. Security, Strategic Dimensions, and International Engagement.

Climate change has direct and indirect consequences on Cyclones, floods, droughts, heatwaves, inundation of low-lying coastal areas, extreme events, flooding, and sea level rise are becoming more extreme around the Indian Ocean, with anthropogenic climate change increasingly impacting weather patterns and threatening marine and terrestrial resources it is important that the developments in ocean science and technology need to be tuned to facilitate the climate change actions and frameworks within the informed decision-making capability of the Government and in making policies and regulatory 112 laws to deal with the varied interests in the oceans and coasts. The ocean is a storehouse of energy, a controller of weather and climate, and underpins life on Earth. However, that relationship is never changing. India has been a global leader in some of the focused approach areas to serve its national goals. The following regulations, frameworks, and guidelines were already formulated in India to accelerate the pace.

1. Island Protection Zone (IPZ) Notification,
2. Integrated Coastal Zone Management (ICZM),
3. Mangroves for the Future (MFF), Coastal Regulation Zone (CRZ) Notification 2011,
4. Reference Manual on Climate change adaptation guidelines for coastal protection and management

An integrated approach needs to be adopted for improvement in quality of life with a focus on skill building and training, upgrading of technology in traditional professions, and specific and time-bound action plans for improving physical and social infrastructure in collaboration with the coastal states. There is growing societal demand for monitoring, understanding, and predicting the state of the Indian Ocean and its climatic influences in a time of accelerating changes and rapid growth.

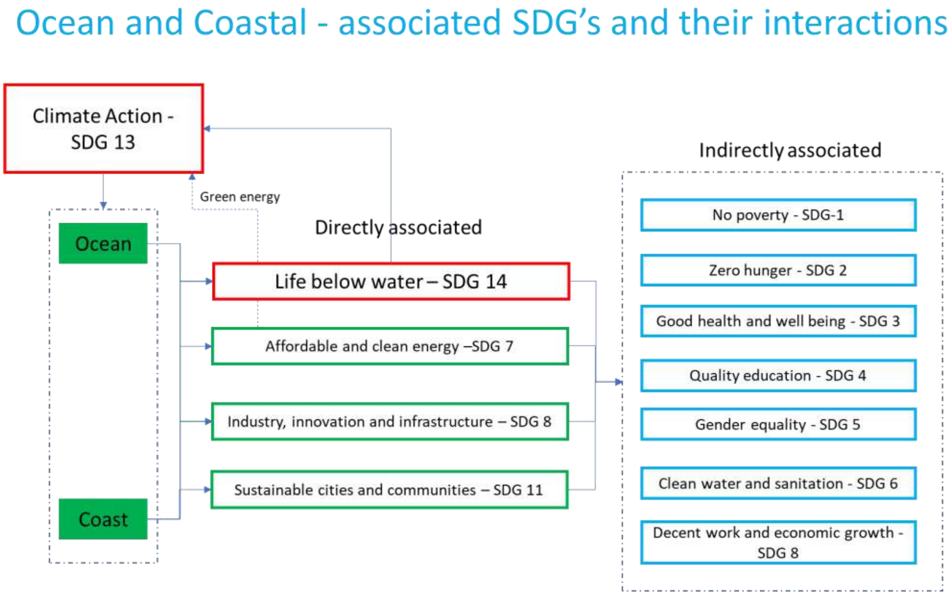


Fig 9.12: SDGs associated with Coastal Processes and Oceans

Goals

Climate change impacts (over and above the natural wave, wind, and physical coastal dynamics) threaten all these essential sectors which are already subjected to numerous direct and indirect pressures. Substantial anthropogenic and environmental pressures have contributed to sediment deficits, excessive erosion, increased sedimentation, and decreased water and environmental quality along the coast. The mission will be forming an inter-institutional, and inter-ministerial and will need policymakers, industry, academia, and research organizations, all contributing their individual strengths towards meaningful larger deliverable goals. Establishing a **National Ocean and Coastal Climate Mission, State Ocean and Coastal Climate Mission and District Ocean and Climate Mission (Regional)** will not only conserve the coastal environment but also promote development, generate revenue, and provide employment. The National Ocean and Coast Climate Mission will include all Phases of other existing Projects agendas incorporating the climate actions which are already established for achieving the national goals. A large-scale result-oriented project will pay the best dividends rather than dealing with open-ended locally distributed research at individual levels approach if the developmental efforts are restructured with adequate resources, it will harness the already available expertise in the country, supplement their gaps, resolve the shortcomings, and lead them to achieve larger goals at an accelerated pace.

Coral reef Observation and Protection

Coral reefs are one of the most biologically diverse marine ecosystems on Earth. Corals grow over geological time scales and have been in existence for about 200 million years. Corals reached their current level of diversity 50 million years ago. Coral reefs play an important role in the marine ecosystem and support the habitats of flora and fauna in the sea. Ecologically, coral reefs are important because they are the counterpart to the tropical rainforest in terms of species diversity and biological productivity in the Ocean. The vast diversity of animal and plant species that contributes to its system and the genetic heritage that it represents are increasingly at risk, in the last few decades. Coral reef enables the formation of associated ecosystems which allow the formation of essential habitats, fisheries, and livelihoods. In addition, coral reefs are climatologically important because they provide an accurate long-term record of climate change and help in extending our knowledge of seasonal climate variability in many remote tropical oceans. Currently, there are many global initiatives such as the Global Coral Reef Monitoring Network (GCRMN), Global Coral Reef Alliance (GCRA), and International Coral Reef Initiative (ICRI) playing an important role in monitoring the reef zones and raising awareness in the public. To increase awareness regarding the importance of reefs, the ICRI has declared the year 2008 as the International Year of the Reef. Similarly, the Ministry of Environment and Forests (MoEF), India has included studies on the coral reef under the Coastal Zone Studies (CZS). Satellite Oceanography is the feasible cost-effective technology to address the mapping and monitoring aspects of the coral reefs. Coral reefs are present in the areas of the Gulf of Kutch, the Gulf of Mannar, Andaman & Nicobar, Lakshadweep Islands, and Malvan. Coral eco-morphological maps were produced using satellite imageries for Andaman & Nicobar, Gulf of Kutch, Gulf of Mannar, and Malvan areas produced in 1:25,000 scales. These maps indicate the condition of corals, density, etc., and will be baseline information. It is important to bring out such maps at a periodical frequency for comparing the conditions and the extent of the corals and for taking appropriate action to protect the coral ecosystem in case of coral acidification due to anthropogenic climate change factors.

Fisheries, Coastal Aquaculture and Coastal Algal Bloom Observation

About 7 million people living along the Indian coastline, spanning over 8100 km, are depending on fishing for their livelihood. Locating and catching fish is always a challenging task. Often, the search for fish ends up in spending considerable time and resources, thus increasing the cost and leading to low profitability. A reliable and timely advisory on the potential zones of fish aggregation will benefit the fishing community to reduce the time and effort spent in searching the shoals of fish, thus improving the profitability and hence, the socio- economic status. The Coastal Aquaculture authority (CAA) was established under the Coastal Aquaculture Authority Act, 2005 and notified vide Gazette Notification dated 22nd December 2005. The main objective of the Authority is to regulate coastal aquaculture activities in coastal areas to endure sustainable development without causing damage to the coastal environment. The Authority is empowered to make regulations for the construction and operation of aquaculture farms in coastal areas, inspection of farms to ascertain their environmental impact, registration of aquaculture farms, fixing standards for inputs and effluents, removal or demolition of coastal aquaculture farms, which cause pollution etc. The increasing frequency of algal blooms is a major concern due to its ill effects on the fishery, marine life, and water quality. It is important to detect and Monitor of Bloom in the Indian Seas which helps the targeted users are fishermen, fishery resource managers, researchers, ecologists, and environmentalists. The duration and magnitude of algal blooms provide essential information for fishery management (Legendre 1990). Therefore, the bloom information also complements the Potential Fishing Zone advisories. Tunas are highly migratory and commercially important species. In order to be able to manage our Tuna resources in a skilled manner, data on the habitat preferences and migration routes of Tuna is very important. Considering the gaps in the knowledge of the habitat preferences and migration routes of Tuna in the Indian Ocean, an R&D project entitled. Satellite Telemetry studies on migration patterns of Tunas in the Indian Seas (SATTUNA) were initiated.

Sedimentation and resource management

It is estimated that over 100 rivers flow into the sea along the Indian shoreline. These rivers play an important ecological role, nourishing the beaches with sand and building complex sedimentary systems, sculpted by physical coastal dynamics. Intense unregulated sand mining activities, primarily for building construction purposes in the river mouths, have resulted in severe environmental degradation and have negatively impacted the ecological integrity of these coastal systems. The scientific audit of the Indian coast conducted during earlier studies has highlighted those nationwide strategies, research and evidence-based decisions, and better planning are urgently needed to protect India's coastline. Coastal remediation is expensive and requires regular maintenance. Hybrid management systems having a combination of hard and soft structures with beach nourishment are viable under different climate change scenarios.

Coastal Industry and City planning

Industrialization and urbanization of the coast create further demand for well-planned coastal management for the changing climate. However, emergency responses are still common during a hazardous event that needs to be developed along the coast as the weather and climate patterns are becoming dynamic it is best to build a framework for the coastal districts and Islands in case of any extreme or hazardous event. These ad-hoc and to a certain extent unplanned approaches cannot initiate strategic management which is required, particularly when confronting climate change impacts as the coast remains a key part of livelihoods in the coastal states and supports tourism, livelihoods, and trade.

Coastal and Inland Shipping Interconnectivity

It is important to reduce logistics costs and time for the movement of EXIM and domestic cargo thus reducing the carbon footprint due to logistics. Development of port-proximate industrial capacities near the coast, in future, is a step in this direction. In this regard, the concepts of Coastal Economic Zones (CEZs), Coastal Economic Units (CEUs), Port-Linked Industrial & Maritime Clusters, and Smart Industrial Port Cities have been introduced to have better interconnectivity between each port. Despite having an extensive network of inland waterways in the form of rivers, canals, backwaters, and creeks freight transportation by waterways is highly under-utilized. Waterways currently contribute around 6% to India's transportation modal mix, which is significantly less than that in developed economies and some of the developing economies as well. It is estimated that coastal shipping traffic of about 250 MMTPA can be achieved from current and planned capacities across coal, cement, iron, and steel, food grains, fertilizers, POL by 2025. Additionally, about 125 MMTPA of cargo is expected to be moved via inland waterways by 2025. The availability of dedicated infrastructure will go a long way in promoting coastal shipping as a mode of freight transportation. Hence infrastructure at ports and supporting infrastructure using rail/road and waterways to facilitate coastal movement are being created. These include the development of dedicated coastal berths, bunkering, and storage at ports, and the creation of supporting hinterland transport infrastructure with last-mile connectivity, having made all these networks, interconnectivity improvements not only develop the Indian Economy it will adversely reduce the carbon footprint which directly helps in the national mission towards climate change.

Coastal Ecotourism

Ecotourism is now globally recognised as a powerful tool for the conservation of ocean, Coast, forests, biodiversity/ wildlife, and scenic landscapes. It does so by creating sustainable alternative livelihoods for forest, Coast, and ocean-dependent communities and by generating conservation awareness among the masses and decision-makers. To strengthen community control and management of the forests, Coast, and ocean, it is important to generate a sustainable flow of non-extractive financial benefits of forests, coast and ocean for the communities, to ensure that the communities take interest in the conservation of forests, coast, ocean and wildlife. Ecotourism is perhaps the only means of achieving this end. Apart from its conservation and economic value, public interest in nature-based recreation, i.e. Ecotourism is fast increasing, and it is the duty of the government to provide this service to the public as far as compatible with conservation imperatives. Ecotourism is one of the fastest-growing segments of the travel and tourism industry which is one of the highest producers of global wealth and employment. National Strategy on Sustainable Tourism the Ministry of Tourism has also drafted a National Strategy on Sustainable Tourism which focuses on promoting environmental sustainability, protecting biodiversity, promoting economic sustainability, and promoting socio-cultural sustainability. The strategy aims to mainstream sustainability into the tourism sector. Ecotourism and Adventure tourism are the important segments to promote sustainable tourism.

Coastal Disaster risk reduction

India suffered USD 79.5 billion economic loss due to climate-related disasters in the last 20 years, according to a UN report which highlights the impact of extreme weather events on the global economy. The global economy suffered a loss of $232 billion (Rs 16.5 lakh crore) due to natural disasters in 2019. In the period 2000 to 2019, there were 7348 major recorded disaster events which took 1.23 million lives and affected 4.2 billion people. These data reflect how deeply the disasters are affecting the life-scapes of human beings. In terms of environmental loss such as loss of soil cover, loss of flora and fauna, and loss of ecosystem the damage is much more. Hazards are a natural process and are bound to occur considering the nature of the lithosphere, atmosphere and hydrosphere which is ever-changing. However, the increase in the occurrence of hazards and disasters is the result of human actions and human interference with the natural process of the earth. Therefore, it is the responsibility of human beings to take prompt and swift action for not only prevention and reduction of disaster but also the revival of earth where there would d be the coexistence of all beings. Losses due to natural disasters cannot be zeroed down but they may be mitigated, and reduced by blending ancient and existing knowledge, and by managing risk through various structural and non-structural strategies. In this respect, many great initiatives have been taken by various stakeholders around the world such as Yokohama Strategy for a Safer World in 1994 for setting up guidelines for natural disaster prevention, preparedness and mitigation and Sendai Framework for Disaster Risk Reduction in 2015-2030. The Sendai framework brought a significant shift from an earlier emphasis on disaster management to addressing disaster risk management itself by emphasizing the underlying drivers of risk. These conferences recognise that the state has the primary role to reduce disaster risk, but that responsibility should be shared with other stakeholders including local government, the private sector, and other stakeholders. Disasters have the potential to destroy decades of investment and effort and cause the deviation of resources intended for primary tasks such as education, health, and infrastructure. Disaster management is therefore an important component of coastal urban planning and management as disasters pose a serious threat to sustainable development. In sum, the physical systems act as the body of the city and if suffer major breakdowns which cannot be repaired, losses escalate, and recovery slows. A city without a resilient physical system will be extremely vulnerable to disasters. Thus, the impacts of disasters can be reduced through pre-disaster activities and a coordinated strategy or plan. The capacity of a system to minimize the probability that a crisis occurs, absorb the effects of a disaster, and ensure quick recovery can be termed resilience. Another aspect in which resilience can be viewed as the system’s ability and preparedness to respond, adapt to the changes with time, and cope, while at the same time maintaining its basic functions and foundational structures There are four factors of resilience: ecological, social, governance and economical. Governance resilience (institutional) is a governance structure which has a flexibility factor which allows adaptation and learning for change. The ability of a system to learn and adapt in times of trouble and to absorb disturbance to become more dynamic and grow can be considered resilience. Disaster mitigation practice has its overriding goal to develop resilient cities, with emphasis on a holistic and integrated approach concerned with connections and relationships, not just structural integrity of infrastructures, buildings, or communities. future mitigation programs must also focus on teaching the city's social communities and institutions to reduce hazard risks and respond effectively to disasters since they will be the ones most responsible for building ultimate urban resilience.

VII. RENEWABLE ENERGY

Ashwin K Seshadri

BACKGROUND

At the 27th Conference of parties of the UNFCCC (COP26), India reiterated its policy to "prioritize a phased transition to clean energy and lower household consumption to achieve net zero emissions by 2070". The country is on track to meet its target of reducing the emissions intensity of GDP by 45 percent (compared to the 2005 baseline) and making half of its installed electricity capacity non-fossil, with present renewable capacity including hydropower approaching 40 percent (MNRE, 2022). Given its low per capita energy consumption, an imperative will be to meet rapidly growing development and corresponding energy needs in a carbon-constrained world.

Wind and solar power are the largest sources of future renewable growth, with abundant solar energy throughout much of the country but regionally specific wind concentrated in southern and western India. Wind resource is also seasonal and tied to summer monsoon flows. Worldwide, substantial cost reductions in renewable energy generation have occurred. Still, electricity from renewables is non-dispatchable, i.e., it cannot be turned on or off to follow electricity demand, since it depends on weather conditions (Shukla et al., 2022). The challenge is expanding renewable energy, given its seasonality and variability, strengthening the national grid to allow the nationwide exchange of electricity, and developing large-scale electricity storage to smoothen the mismatch between instantaneous demand and variable and intermittent renewable energy supply. Over time, fossil fuel sources will have to decline, and hydroelectric power is limited to a few regions of the country, so a future low-carbon electricity system for India will require large-scale energy storage, especially as transportation and building energy use are increasingly electrified. Furthermore, some industrial sectors (e.g., steel) are difficult to decarbonize and electrify, requiring the development of a hydrogen-fuelled economy using new techniques.

Current Status

Following the recognition of the impacts of short-term weather and long-term climate on important decisions (e.g., resource/impact assessment, site selection, operation and maintenance of energy infrastructure, grid integration, electricity pricing, and insurance), the demand for climate information and analytics services by the energy industry is growing (Troccoli and WMO, 2015). The development and standardization of high-resolution climate datasets, the proliferation of assimilation and forecasting products, and the expansion of industry-specific analytics and software support this. At the same time, climate services and climate science research are closely linked, with climate sciences increasingly alert to their applied roles in climate services and decision-making.

In India too, the energy services sector has been expanding rapidly, and ranges from strategic planning of energy systems to hourly forecasting of generation at the site-level. India Meteorological Department (IMD) numerical weather forecasts and high-resolution regional climate modelling play an important role. Notably, unlike other classic local-downscaling approaches conventionally employed, the renewable energy sector also offers the unique demand for network-scale forecasts: ultimately electricity demand and supply must be balanced at the grid scale. Renewable energy forecasting is increasingly outsourced to qualified coordinating agencies, who make forecasts of aggregate generation on behalf of many operators in the state or regional network. System-level services (e.g., network-level forecasting) for the renewable energy sector are an important area of future development (Figure 9.13). Renewable energy variability and extreme events are also affecting grid management, especially when producing energy droughts at the grid scale.

Context

- Ambitious decarbonization goals for India's energy sector
- Wind and solar largest sources of renewable growth
- Widespread solar resources, regional (and seasonal) wind
- Renewable generation is non-dispatchable and variable
- Renewable capacity growth requires targeted climate science

Current Status

- Growing energy sector demand for climate information and analytics
- Wide range of applications in India: from strategic planning to hourly to day-ahead generation forecasting
- Forecast aggregation plays a growing role
- System-level services important to future development
- Generation variability at network scale (and energy droughts) are challenging

Objectives

- Understand sector-specific budgets for resource assessment
- Nested modelling and high-resolution studies
- AI/ML applications: NWP model improvement, statistical (e.g., "generative" models), downscaling
- Expand wind and solar measurements as a public good
- Encourage widespread availability of generation measurement from plant data acquisition systems

Roadmap

- Resource assessment, grid-integration, and uncertainty quantification studies to support long-term investments
- Expanded high-resolution modelling for supply and demand-side assessments
- Expanding availability/use of weather and plant data
- Improved applications of AI/ML to network-scale problems
- Expanding collaboration for high-resolution, nested, and hierarchical modelling

Figure 9.13: Climate services for the renewable energy sector in India.

Role of climate science

Therefore, climate science plays an important role in the energy transition: for understanding renewable resource distribution; variability/intermittency on second to interannual timescales; effects of climate change on resource availability and variability; synergies between resources and with patterns of electricity load; estimating capacity requirements for ancillary services including energy storage; predictability and generation forecasting hours to days ahead; and understanding physical risks to energy infrastructure (both fossil and non-fossil energy) from extreme weather events.

For solar-powered electricity, growth in ground-mounted solar photovoltaic (PV) panels will play a major role, with rooftop solar panels also contributing. PV generation depends mainly on shortwave radiation (direct and diffuse) near the surface, with a secondary effect of temperature PV cell efficiency. Shortwave radiation depends on the solar zenith angle and its seasonal evolution and cloud cover, causing generation variability at a wide range of frequencies. Clouds are poorly represented in numerical weather prediction (NWP) and climate models (Hong and Dudhia, 2012). Model improvement will have corresponding benefits for solar power.

As for wind, since horizontal-axis turbines will mainly contribute to its growth in the coming decades, understanding the horizontal kinetic energy budget and variability of the horizontal wind field (at about 100 meters above the surface, the typical hub height of wind turbines) becomes important. Improved constraints on wind power potential are important for electricity planning as the grid becomes decarbonized. This will require high-resolution (vertical and horizontal) measurements, together with various models. In addition to NWP and coupled climate models, large eddy simulations (LES) are needed for resolving the boundary layer winds and understanding the effects of wind farm configurations. Wind power in India experiences a strong seasonal cycle, with generation practically confined to summer monsoon months, and a low-carbon electricity system must be designed accordingly. Solar power is not produced at night, and large amounts of storage might be required at these hours. Additionally, the effects of projected changes in monsoon circulation and cloud cover due to climate change must be accommodated (Anandh et al., 2022).

Renewable energy droughts pose another challenge (Gangopadhyay et al., 2022). At low windspeeds, wind turbines do not produce electricity. On cloudy days or days with high aerosol, solar generation is lowered. The intensity and duration of regular and common (e.g., seasonal cycle, monsoon intraseasonal variability) as well as episodic (e.g., wind drought events, dust-storms) events can affect a variety of decisions (site selection, grid integration, pricing and insurance, operating reserves, and energy storage, etc.) with larger effects in a low-carbon grid. Electricity consumption is higher in summer, and renewable energy droughts in these months can pose difficulties.

High-resolution global modeling of renewable energy resources, complemented by in-situ and satellite observations, will play a growing role. Kilometer-scale modeling is widely viewed as an important frontier. For tropical regions, this would resolve deep convection, which is currently parameterized in present global coupled climate models due to their much coarser resolutions. Storm-resolving models approaching the kilometer scale resolve the diurnal cycle, and various experiments involving both global and regional models can reveal important features (Stevens et al., 2019). For the energy sector, this will impact the understanding of clouds and the radiation budget, and the kinetic energy budget due to the upscale transfer of energy at small scales, including in regions of high orographic gradients.

Since the demand-supply balance in a low-carbon grid has to be addressed at the grid level, nested models of various kinds can help understand scale interactions in climate change and variability. Ultimately electricity grid simulators will rely on various statistical models (e.g., “generative models”) that emulate ensembles of high-resolution model outputs.

OBJECTIVES

- *Climate science and modeling*:

  Resource assessment, grid integration, etc. depend on specific budgets (e.g., boundary layer kinetic energy, shortwave radiation, etc.) to be reported. For applications, outputs of models (e.g., hub-height winds, surface irradiation) must be integrated with electricity grid simulators. High-resolution and uncertainty quantification become important.

  Nested models can provide a unified approach to processes at various spatial and temporal scales. Elsewhere, high-resolution runs (e.g., LES) can provide local information where this is important. Coupled climate models become important beyond weather timescales. The indigenous IITM-Earth System Model can improve the understanding of regional processes under climate change, yielding merged datasets of important variables. Advances in resolution will have many benefits. AI/ML approaches can be used variously: to improve models using observations; develop statistical models from observations, model outputs, and assimilations; and for down-scaling from model to plant scales.

- *Observations and datasets:*

  Sector-specific observations are public goods, e.g., wind measurements at 50-150 meters above ground level and surface solar irradiation. Complemented by satellite-based measurements of atmospheric circulation (e.g., Doppler wind lidar), the availability of such observations is directly useful as well as important for bias correction, assimilation, and gridded merged products for the sector.

  Wind plants and large solar plants have their data acquisition systems, the latter including solar radiation measurements. Such data, if publicly available, can improve the modeling of the link between generation forecasts and NWP model outputs and contribute to the improvement of NWP models. Also, given such a database of local measurements, and consequent generation, downscaling approaches can be developed for weather variables and generation.

ROADMAP

Short term

To expand electricity generation from renewables, resource assessment and grid integration studies, and their uncertainty quantification, are required. Some regions will pose greater modeling challenges (e.g., owing to orography), and these can be identified. Resource assessments can be complemented by model sensitivity studies, analysis of budget variability in model experiments, and "mechanism denial" experiments using various models to support long-period expenditures in renewable energy and corresponding ancillary infrastructure. Resource assessment and variability studies will benefit from the improved resolution of coupled modeling, e.g., in IITM-ESM. Coupled modeling will be important to understand the important offshore wind resource. High-resolution modeling of regional climate change will influence not only the supply side of the energy sector but also projections of how the demand side is influenced.

The energy meteorology observation network can be expanded, and simultaneously generators may be encouraged to make generation data public. Sector-specific high-resolution datasets based on meteorological and generation data can be developed.

Expertise in applying AI/ML to energy forecasting resides with stakeholders (generators, aggregators, etc.), which could give rise to intercomparison exercises of AI/ML and NWP approaches. For short-term prediction a few hours ahead, AI/ML can be cheaper than running NWP. AI/ML can also be used to develop generative models or emulators for various energy applications. Such models will have to be trained on weather and climate data, as well as modeling output. Developing model experiments and observations to improve and validate generative models would be important.

Long term

High-resolution Earth system models will develop slowly and over decades. Understanding the extended range and beyond will advance through improvements in the resolution of coupled modeling. Eddy-resolving ocean models show improvements in simulating near-surface wind and could become important to understanding changing weather on climate timescales. Such advances should be fully exploited. An improved understanding of cloud physics and modeling will benefit the sector.

Developing modeling hierarchies for a better understanding of regional meteorology and climate can also contribute to the renewable energy sector: from high-resolution regional weather models providing an improved understanding of short-term variability and prediction, and improvements in LES and nested modeling aiding better estimates of the local wind fields and wind resources.

At better resolution, one does not simply resolve more scales and their interactions but also approximates more realistic model output datasets that can be more directly compared with various observations (including point measurements of wind speed, etc.). The utility of climate modeling is not limited to model outputs, but also their role in constructing generative models and emulators. This requires wide collaboration.

Summary

As India's renewable energy capacity grows, weather and climate science will play a crucial role in energy-specific services, such as identification (site selection and capacity estimation), planning (storage assessment, transmission/distribution investments, ancillary infrastructure, insurance), and operations. Broadly, these involve physical understanding, providing support for good choices, and developing a basis for exploring a variety of weather and climate scenarios.

On shorter timescales, electricity dispatch, unit commitment, and scheduling and pricing depend on forecasting hours to days ahead. Given the importance of synoptic and mesoscale variability for various aspects of renewable energy generation, numerical weather prediction and coupled climate models will grow in importance for India's energy sector. At the same time, NWP and climate models are imperfect, with many unresolved processes. There is a growing appreciation of how large data and machine learning can complement the physical laws approximated by these models. Each of the above applications will benefit from expanded Earth system observations as well as sector-specific variables and pooled and standardized datasets (Earth observations + generation output) from plant sites.

Weather and climatic information are also needed at various spatial scales from individual generators, pooling stations, and regional/national grids. Climate science in its various aspects, from Earth system observation and analysis, Earth system model development, model intercomparison and theory development, and building statistical emulators, will contribute significantly to the evolving energy sector. Ultimately, moving towards a low-carbon electricity system is a multidisciplinary effort, and climate science must engage widely to contribute to a just transition.

REFERENCES

Anandh, T. S., D. Gopalakrishnan, and P. Mukhopadhyay (2022), Analysis of future wind and solar potential over India using climate models, *Current Science*, 122, 1268-1278, doi: https://www.currentscience.ac.in/Volumes/122/11/1268.pdf

Gangopadhyay, A., A. Seshadri, N. Sparks, and R. Toumi (2022), The role of wind-solar hybrid plants in mitigating renewable energy droughts, *Renewable Energy*, 194, 926-937, doi: https://doi.org/10.1016/j.renene.2022.05.122

Hong, S.-Y., and J. Dudhia (2012), Next-Generation Numerical Weather Prediction: Bridging Parameterization, Explicit Clouds, and Large Eddies, *Bulletin of the American Meteorological Society*, 93, ES6-ES9, doi: 10.1175/2011BAMS3224.1.

MNRE (2022), Renewable energy in India. https://pib.gov.in/

Shukla, P. (Ed.) (2022), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, chap. IPCC, 2022: Summary for Policymakers, pp. 1-52, Cambridge University Press.

Stevens, B., M. Satoh, and L. Auger (2019), DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains, *Progress in Earth and Planetary Science*, 6, 1-17, doi: 10.1186/s40645-019-0304-z.

Troccoli, A., and WMO Secretariat (2015), Climate Services for the Energy Sector: A New GFCS Priority Area.https://public.wmo.int/en/resources/bulletin/climate-services-energy-sector-new-priority-area-gfcs

Sector-Specific Climate Services - CONCLUDING REMARKS

Climate services in India has a history of development for more than 150 years. In the recent years the challenges and opportunities in climate services have increased to a great extent. The climate risk has increased to a large extent due to threats associated with climate change. The regional impacts are also uncertain to a large extent. Hence, the improvement in services through better research collaboration has become a necessity. This chapter highlighted and brought out some challenges in application of climate services in several sectors. The near future goals (defined as vision 2030) are described for some priority sectors like agriculture, water, health, renewable energy, coastal management, climate resilient infrastructure development, and disaster risk mitigations. The authors stressed about multi-disciplinary approach associated with climate services. The collaborative research and institutional handholding are a necessity to improve such interdisciplinary applications of climate services in several sectors. While these verticals would benefit from the research work, successful implementation of climate service strategy is very important. The effective application of forewarning techniques must be popularized keeping in mind the diversity of stakeholders. Reaching the last mile is a challenge and such collaboration would help developing the climate smart sectorial services to a large extent.

SUMMARY & CONCLUSIONS

The irreversible global climate change has resulted in significant adverse impacts in every region around the globe. The highly populated South Asia, including India, is largely affected in different sectors. The climate is an inseparable component of the human-natural system. Hence, any scientific or technological development should have a strong climate component on the path of sustainability and resilience. Addressing climate change when we are on the development pathways needs a good understanding of the climate system, specifically the tropical climate of India. Hence, the present report starts with a detailed review of scientific developments in climate science covering the atmosphere, biosphere, and hydrosphere, their modeling and how they can collectively contribute to the climate services for improving climate resilience.

With technological development, climate modeling and understanding have improved at a regional scale at a finer resolution; however, challenges, such as extremes, cloud parameterization etc. remained. Hence, the climate research challenges are bi-directional, the first is to develop and improve understanding and modeling of climate processes, and the second is to use the existing state of the art with uncertainty to develop climate services (Figure 10.1). One key research need identified by the report is to develop India-specific climate modules for modeling the Indian human-natural system, which differs from the Western countries.

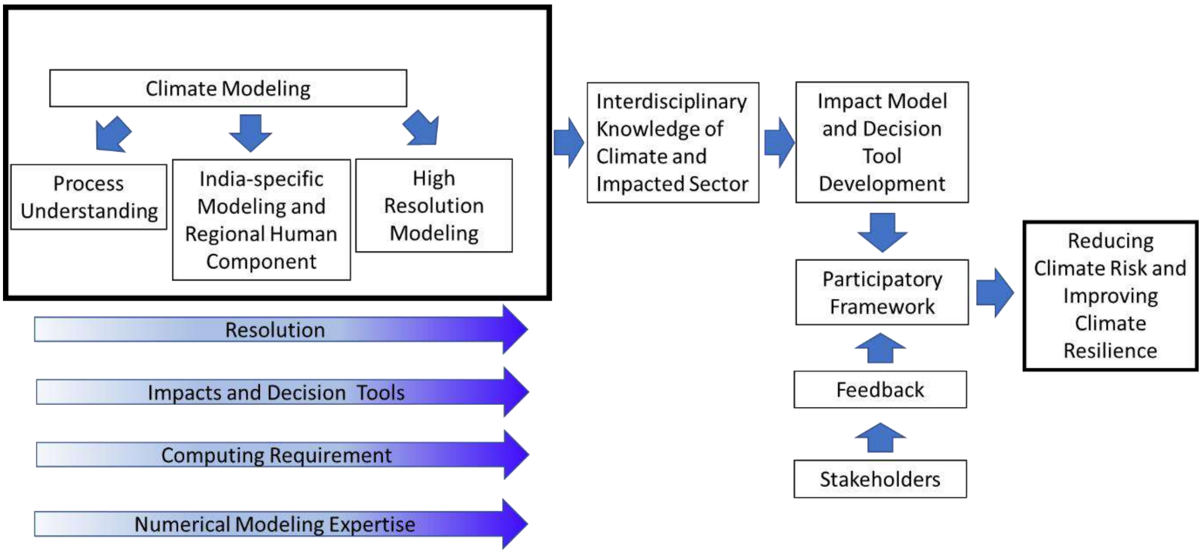


Figure 10.1: Climate Modeling to Climate Services

The report also identifies significant overlap across the themes (Figure 10.2), which needs multi-disciplinary, multi-institutional research, precisely the academia-national lab-industry joint research initiatives. The development of climate services needs a participatory framework with direct involvement from the stakeholders and a procedure for getting their feedback. With a collective effort, India has a huge potential to develop sustainable pathways for climate-resilient development with an improved understanding of monsoon, better modeling of climate components, development of the participatory models and utilizing the opportunity of implementation to socio-economically and ecologically varying case studies.

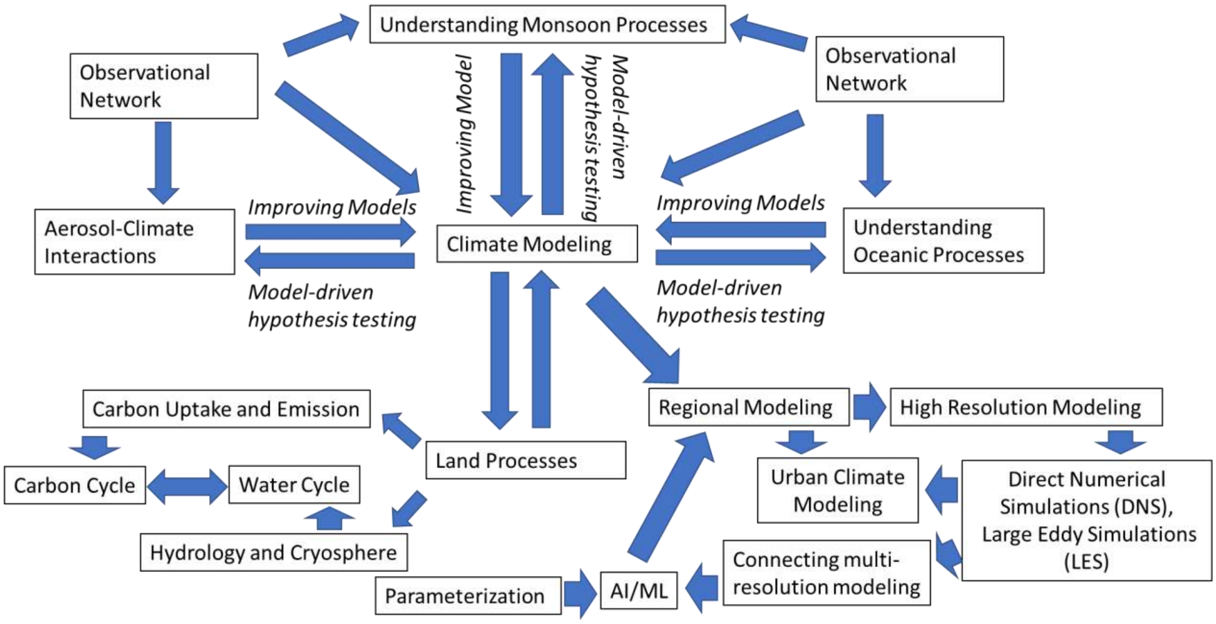


Figure 10.2: Cross-disciplinary Climate Themes and Research Areas

- END –

Ministry of Earth Sciences (MoES)
&
Department of Science and Technology (DST)
(Govt. of India)

jointly present

INTERNATIONAL CLIMATE RESEARCH CONCLAVE (ICRC) 2023 | 26-27 May 2023

About ICRC 2023

Anthropogenic greenhouse gas emissions have resulted in unprecedented, intensifying and irreversible global warming. An economically ascendant India will face the brunt of the impacts of climate change, namely increasingly more frequent extreme events affecting our water, agriculture, infrastructure and health. The development of a climate-resilient India thus requires fundamental insights in climate science, technological innovation for climate adaptation, and climate-aware policy formulations. This Conclave will bring together researchers to discuss India's recent progress in all areas of climate research, as well as the agenda for future research and a vision for 2030 and beyond.

PATRONS

Dr. M. Ravichandran	Secretary, MoES
Dr. Srivari Chandrasekhar	Secretary, DST
Prof. Subhasis Chaudhuri	Director, IIT Bombay
Prof. K. V. Krishna Rao	Deputy Director, IIT Bombay
Prof. S. Sudarshan	Deputy Director, IIT Bombay

NATIONAL CORE COORDINATION COMMITTEE

Dr. Akhilesh Gupta	Secretary, SERB & Senior Adviser, DST
Dr. Anita Gupta	Scientist 'G', DST
Dr. Nisha Mendiratta	Scientist 'G', DST
Dr. Gopal Iyengar	Scientist 'G', MoES
Dr. Susheela Devi Negi	Scientist 'E', DST
Prof. Subimal Ghosh	IIT Bombay

SCIENTIFIC COMMITTEE

Dr. Akhilesh Gupta	Secretary, SERB and Senior Adviser, DST
Dr. R Krishnan	Director, Indian Institute of Tropical Meteorology Pune
Dr. K S Hosalikar	Scientist 'G' & Head, Climate Research & Services, India Meteorological Department
Dr. M V Ramana Murthy	Scientist G & Director, National Centre for Coastal Research
Dr. Anita Gupta	Scientist 'G', & Head, Innovation and Entrepreneurship & Technology Mission, DST
Dr. Nisha Mendiratta	Scientist 'G' & Head, WISE-KIRAN Division, DST
Dr. Tummala Srinivasa Kumar	Director, Indian National Center for Ocean Information Services
Prof. V Geethalakshmi	Vice Chancellor, Tamil Nadu Agricucltural University, Coimbatore
Prof. R K Mall	Banaras Hindu University, Varanasi
Dr. Abhisek Chatterjee	Scientist 'E', Indian National Center for Ocean Information Services
Prof. S A Sannasiraj	IIT Madras
Dr. Saroj Kanta Mishra	IIT Delhi
Dr. V S Prasad	Scientist 'G', National Centre for Medium Range Weather Forecasting
Prof. Sagnik Dey	IIT Delhi
Prof. A K Sahai	Indian Institute of Tropical Meteorology Pune
Prof. Ashwin Seshadri	IISc Bangalore
Prof. Vimal Mishra	IIT Gandhinagar
Prof. Udit Bhatia	IIT Gandhinagar
Prof. Pankaj Kumar	IISER Bhopal
Prof. V Vinoj	IIT Bhubaneswar
Prof. Suneet Dwivedi	University of Allahabad
Prof. Rajesh Kumar	Central University of Rajasthan
Prof. Sandeep Pattnaik	IIT Bhubaneshwar
Prof. Arindam Chakraborty	IISc Bangalore
Prof. Manish Kumar Goyal	IIT Indore
Prof. Anil Kumar Gupta	National Institute of Disaster Management
Prof. Subhankar Karmakar	IIT Bombay
Prof. Subimal Ghosh	IIT Bombay

LOCAL ORGANIZING COMMITTEE

(Interdisciplinary Programme in Climate Studies (IDPCS), IIT Bombay)

IDPCS, IIT Bombay Faculty

Prof. Subimal Ghosh

Prof. Subhankar Karmakar

Prof. Karthikeyan Lanka

Prof. Riddhi Singh

Prof. Vishal Dixit

Prof. S Ravichandran

Prof. Angshuman Modak

IDPCS, IIT Bombay Staff

Archismita Banerjee

Sheeba Sekharan

Dr. Sanghita Basu (Culturals)

Ganesh Gupta

Kalyani Sonawane, Harsha Kharpade

Teklal Kumar

Balika Savalkar

IDPCS, IIT Bombay Students

LEAD STUDENT COORDINATORS - Priyam Prasambit Tripathy, Khandare Ajinkya Mohan

LOGISTICS & ACCOMODATION COORDINATORS – Dr. Siddhesh Ashok Tirodkar, Priyam Prasambit Tripathy, Khandare Ajinkya Mohan, Sachin Budakoti, Chauhan Rajesh Omkumar, Chimurkar Navinya Dilip, Girish Patidar, Manish Kumar Dhasmana, Roshan Jha, Gaurav Ganjir

FOOD COORDINATORS - Priyam Prasambit Tripathy, Khandare Ajinkya Mohan, Subhashis Chowdhury, Sabirul SK, Mohan Sarkar

TECHNICAL COORDINATORS – Dr. Taveen Singh Kapoor, Tejasvi Chauhan, Ripan Das, Ganesh Gupta, Vishnu U Krishnan, Muhammed Rashid, Akash Verma, Vikas Kumar

DESIGN TEAM - Tundia Krutika Rajesh, Tannu Kaushik, Achanya Lakshmanan, Pooja Manwani, Puja Tripathy, Priyam Prasambit Tripathy, Aiswarya C L, Vikas Kumar, Sachin Budakoti

CULTURALS TEAM – Dr. Sanghita Basu, Tundia Krutika Rajesh, Ankan Chakraborty, Shinde Reshma, Tannu Kaushik, Ripan Das

BROCHURE TEAM - Tundia Krutika Rajesh, Tannu Kaushik, Ganesh Gupta, Zinia Kar, Sheeba Sekharan

PHOTOGRAPHERS – Ripan Das, Roshan Jha

ICRC EVENT ANCHORS - Debasmita Majumder, Matrika Ghimiray, Tannu Kaushik, Reshma Shinde

RAPPORTEURS - Roshan Jha, Sachin Budakoti, Vikram Chandel, Taveen Singh Kapoor, Navinya Chimurkar, Rajesh Chauhan, Aryalakshmi, Debasmita Majumder, Pallavi P, Nivedita Dubey, Akash Verma, Leena Khadke, Ankan Chakraborty, Achanya Lakshmanan, Puja Tripathy, Soumyashree Dixit

OTHER VOLUNTEERS - Subhashis Chowdhury, Sabirul SK, Mohan Sarkar, Anokha Shilin, Sayantan Mandal, Chanthingla Horam, Sohana Debbarma, Debdatta Chakraborty, Aiswarya S L, Ajay Devda, Elizabeth Eldhose