Chandra Venkataraman
Trupti Mishra
Subimal Ghosh
Subhankar Karmakar *Editors*

Climate Change Signals and Response

A Strategic Knowledge Compendium for India

Springer

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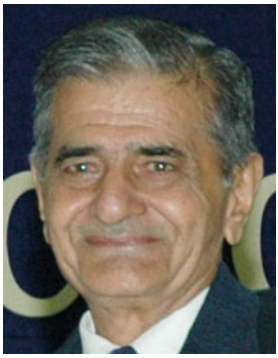

Prof. D. R. Sikka (1932–2017)

For his generosity in bestowing his science and his conviction on the DST-Centre of Excellence in Climate Studies Indian Institute of Technology, Bombay

Prof. Dev Raj Sikka, known as the "Monsoon Guru", was born in 1932 in Jhang Mighiana, in then undivided India, now Pakistan. Prof. Sikka joined the India Meteorological Department (IMD) in 1954 before moving to the Indian Institute of Tropical Meteorology (IITM) in Pune in 1962, becoming its Director in 1986. His contribution to the field of Indian Monsoon is beyond comparison. His passion for monsoon research and his breakthroughs in monsoon science merged the contributions of pioneers of Monsoon Meteorology—Blanford, Elliot, Walker, Riehl, Malkus, Anantha Krishnan, Bjerknes and Charneyto—to generate our current understanding of monsoon science and mechanisms. He employed traditional and space-borne observations over India within the context of well-conceived theoretical frameworks. This led to his discovery of coherent northward propagations of precipitation band over the equatorial Indian Ocean at intervals of 2–6 weeks, throughout the summer monsoon season of June to September, leading to improved forecasting of intra-seasonal variations. Prof. Sikka's work on the link between the Indian summer monsoon rainfall and ENSO is the basis of monsoon prediction by most of the state-of art dynamical models, even today. Prof. Sikka was elected a Fellow of the Indian Academy of Sciences in 1984, received the first Lifetime Achievement

Award in Atmospheric Science and Technology from the Ministry of Earth Sciences in 2007, the Sir Gilbert Thomas Walker Gold Medal in 2012 and Lifetime Achievement Award from the India Meteorological Society (IMS) in 2017. The "Monsoon Guru," Prof. Dev Raj Sikka, passed away on 18 March 2017 and is survived by a granddaughter, two daughters and the community of grateful monsoon and climate scientists.

Foreword I

As part of the National Action Plan on Climate Change (NAPCC), the National Mission on Strategic Knowledge for Climate Change (NMSKCC) is one of the eight national missions on climate change coordinated by Department of Science and Technology, through its Climate Change Programme, Strategic Programmes, Large Initiatives and Coordinated Action Enabler (SPLICE) Division. The broad objective of NMSKCC is to build a vibrant and dynamic knowledge system that would inform and support national action on climate change and sustainable development.

The "DST-Centre of Excellence in Climate Studies (DST-CoECS)" at IIT Bombay was initiated and supported by DST under the NMSKCC in January 2012 with the aim to undertake interdisciplinary, problem-driven research for end-to-end solutions covering the causes and consequences of and responses to climate change; to build long-term scientific capacity and systems for study of regional climate change and climate futures; to enable the creation of a pool of multidisciplinary researchers to serve the growing need for climate change scientists and professionals to serve R&D and policy needs in private, public and governmental institutions; and to provide critical assessments to support policy and governmental decision-making on air and water resources and climate mitigation and adaptation measures.

The DST-CoECS has participation of over 24 faculty members from 9 departments of IIT Bombay, who apply their expertise to interdisciplinary problems that cross traditional academic boundaries to address climate change not only through climate and environmental science but also through economics and engineering. Co-advised training of over 30 Ph.D. scholars has been achieved, along with significant enrichment through lecture series and short courses, from invited national and international experts. It is heartening that the Centre has produced significant research output in terms of high-impact international journal publications.

I am happy to note that the Centre is bringing out a book entitled *Climate Change Signals and Response: A Strategic Knowledge Compendium for India* which is a synthesis of the recent research findings in climate change from the

DST-CoECS. The general scope of the book is to chronicle strategic knowledge to inform, guide and support national- and state-level action on climate change.

I am confident that this book will serve as an invaluable tool to disseminate scientific findings to various stakeholders including students, academicians, industry professionals and policy makers as well as to inform general public at large.

I would like to congratulate the DST-CoECS for having brought out such a useful publication and thank the Editorial team and authors for their contributions to the book.

New Delhi, India
March 2018

Dr. Akhilesh Gupta
Advisor and Head, Strategic Programmes
Large Initiatives and Coordinated Action Enabler (SPLICE)
Division and Climate Change Programme
Department of Science and Technology
Ministry of Science and Technology
Government of India

Foreword II

Climate change signals indicate increased climate variability over the Indian region during the last 50 years, which could accelerate during coming decades. We have witnessed extreme temperatures, persistent droughts and frequent floods. Urbanisation, though a worldwide phenomenon driving climate change, is starkly visible in India. Economic growth and development impact emissions of greenhouse gases and short-lived climate pollutants, which drive climate change.

India's Nationally Determined Contributions (NDCs) submitted to United Nations Framework Convention on Climate Change (UNFCCC) is an attestation of our commitment to global environmental concerns. The government is committed to enhancing investments in development programmes in sectors vulnerable to climate change, particularly agriculture and water resources, in ecologically sensitive regions.

The Department of Science and Technology is coordinating and implementing a National Mission on Strategic Knowledge for Climate Change (NMSKCC) under National Action Plan on Climate Change (NAPCC) with a broad objective of building S&T capacity and training of scholars and researchers to generate new knowledge to underpin government decision-making. Under this mission, the DST-Centre of Excellence in Climate Studies, IIT Bombay, was established in January 2012, with an objective to "develop a scientific understanding of regional climate change and connect it to impacts (socio-economic, environment, resources) and effective response (technology and adaptation)". I am happy to see that the Centre has performed well towards meeting these objectives and have shown good research outcomes.

I am pleased to note that some of the key findings of the Centre of Excellence are being brought out as a book entitled *Climate Change Signals and Response: A Strategic Knowledge Compendium for India*. The book attempts to highlight actionable outcomes from the research undertaken, encompassing emergence of regional climate signals, their regional impacts and mitigation and adaptation response, relevant in the Indian context.

I compliment the editors and contributors of the book for their sincere efforts to synthesise high-impact research findings into actionable recommendations and policy prescriptions at national and sub-national levels.

I am confident the book will be of great use to not only researchers working in the area of climate change but also the policy makers who would find some of the findings useful for policy formulation purposes.

New Delhi, India
March 2018

Prof. Ashutosh Sharma
Secretary, Department of Science and Technology
Ministry of Science and Technology
Government of India

Preface and Acknowledgements

The notion for a book synthesising strategic knowledge for climate change action in India arose towards the end of the first phase of the Department of Science and Technology-sponsored Centre of Excellence in Climate Studies (DST-CoECS, 2012–2017) at IIT Bombay. A group of colleagues at IIT Bombay, with diverse expertise and backgrounds, had endeavoured for 5 years to step out of their research comfort zones, cement working relationships with collaborators from disciplines distinct from their own, in keeping with the governing philosophy of the Centre, and engage with rookie Ph.D. scholars to begin to create multidisciplinary, strategic knowledge on climate change in India. In the first phase of the Centre, a substantial body of scientific outcomes was achieved, leading to a large number of high-impact research publications. We then were encouraged by our chief mentor at DST, Dr. Akhilesh Gupta, Adviser/Scientist-G and Head, SPLICE and CCP to go beyond, to try and distil actionable recommendations from the underlying science.

Periodic engagement with the DST Expert Review Committee led alternately to dismay and inspiration, in regard to the enormous task we had set ourselves. The DST Expert Review Committee, especially Prof. D. R. Sikka, to whom we dedicate this volume, injected realism into our endeavours, while providing a strong base of conviction in our vision and work. We sincerely acknowledge Strategic Programmes, Large Initiatives and Coordinated Action Enabler (SPLICE) and Climate Change Programme (CCP), of the Department of Science and Technology, both for foresight in envisaging the Centre and for a crucial seed grant, to enable its set-up and functioning. Importantly, the grant enabled fellowships for over 20 doctoral students, who cemented academic exchange between their faculty mentors. We convey our sincere gratitude to Dr. Akhilesh Gupta, Adviser/Scientist-G and Head, SPLICE and CCP, for his continuous support and encouragement of the research at the Centre. Professor Ashutosh Sharma, Honourable Secretary of DST, has displayed a keen interest in understanding both climate change and air pollution over India. Professor Sharma has provided encouragement through informal discussions at DST workshops and was kind enough to provide a foreword to this book.

At IIT Bombay, the new Interdisciplinary Programme in Climate Studies is home to the DST-CoECS. Institute functionaries at IIT Bombay provided far-sighted and perceptive leadership in setting up one of the first doctoral programmes in climate studies, in India, as an independent academic unit. We thank Director, Prof. Devang Khakhar, and then Dean, Research and Development, Prof. Rangan Banerjee, for their mentoring of the Interdisciplinary Programme in Climate Studies. The editors are grateful to all authors, for their contributions, and for making this a wholesome, cooperative venture. We thank the team of student assistants, Ms. Anjana Devanand, Ms. Piyali Chowdhury, Ms. Krishna Malakar and Mr. Kushal Tibrewal, for their coordination efforts. Ms. Archismita Banerjee, Manager of the DST-CoECS at IIT Bombay, has played a central role at every stage of evolution of the book from coordinating early meetings, to helping with the concept note, to final collation of materials. We appreciate her cordial and patient coordination efforts, which have been central to completion of the work under the required time frame.

The process adopted in developing this book involved consultation meetings of the author group and development of a concept note which, along with sample chapters, was subject to review by our publishers, Springer Nature Scientific Publishing Services (P) Ltd. The completed book manuscript was then subjected to peer review, leading to significant and important inputs towards improvement of the book. At Springer, our sincere thanks are due to their staff, especially Sagarika Ghosh and Nupoor Singh, for their keen interest and time, towards discussions to frame the scope and content of the book. The editors wholeheartedly appreciate the professional support of Springer staff, for a rapid and smooth journey in bringing this book to press.

The structure and framework for any such collaborative outcome are necessarily enriched by broader conversations with peers and mentors. Among these colleagues, CV thanks Dr. Veena Joshi, Prof. Milind Kandlikar and Prof. Ambuj Sagar; TM thanks Prof. Anand Patwardhan; SG and SK both thank Prof. Raghu Murtugudde and Prof. Dev Niyogi; and SK thanks Prof. Dilip Swain and Dr. Naresh Soora. A project of this nature necessarily involves a state of preoccupation, on part of the editors, for a period of time. We thank our families for tolerating any unwitting distraction or inattention, on our parts, during the course of writing.

Mumbai, India

Chandra Venkataraman
Trupti Mishra
Subimal Ghosh
Subhankar Karmakar

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Editors and Contributors

About the Editors

Chandra Venkataraman is a Professor of Chemical Engineering and Associate Faculty at the Interdisciplinary Programme in Climate Studies, IIT Bombay. She works on environmental and climate science and aerosol nanoparticle engineering. Her research has contributed influential scientific knowledge on black carbon aerosols, climate change and air quality degradation over South Asia. She has built research networks for climate and air quality studies. She is the National Coordinator of the NCAP-COALESCE project leading 17 institutions investigating regional climate impacts of carbonaceous aerosols (MoEFCC). At IIT Bombay, she was instrumental in the establishment of Interdisciplinary Programme in Climate Studies and was Principal Investigator of the DST-supported Centre of Excellence in Climate Studies. She is the recipient of a Fulbright-Nehru Research Fellowship (2012), Vikram Sarabhai Award (2005), Fellowship of the Indian National Academy of Engineering (2016), the National Academy of Science, India (2017), and the Indian Academy of Science (2017).

Trupti Mishra is an Associate Professor at Shailesh J. Mehta School of Management and Associate Faculty at Interdisciplinary Programme in Climate Studies, IIT Bombay. She holds a Ph.D. in Economics from IIT Kharagpur. Her research interest is focused on economics of pollution, economic assessment of climate change vulnerability, adaptation and mitigation options and corporate environmental sustainability. Her research involves developing different low carbon scenario in sectors, identifying cost-effective mitigation option for industry, suggesting environmental compliances measures to achieve low carbon growth. She has published her research findings in various chapters and journal papers. She is also working on climate change impact and adaptation at city and community level. Her co-authored 2017 publication in *Climate and Development* (Taylor & Francis) on assessing the socio-economic vulnerability of cities in India received wide mainstream media coverage.

Subimal Ghosh is an Associate Professor at the Interdisciplinary Programme in Climate Studies and a Faculty at the Department of Civil Engineering, IIT Bombay. He works in the area of hydro-meteorology. His research interests include climate change impact assessment with statistical downscaling, understanding land surface feedback to monsoon, hydrological simulation and urban extreme rainfall forecasts. He has received several awards in recognition of his research, a few among them being INAE Young Engineer Award, INSA Young Scientist Award, NASI Young Scientist Award and IEI Young Engineer Award. He has published articles in reputed journals such as *Nature Climate Change*, *Nature Communications*, *Scientific Reports*, *Geophysical Research Letters*, *Journal of Climate*, *Water Resources Research*. He has been selected as one of the lead authors for IPCC Assessment Report 6 for a chapter on extremes by Working Group-I.

Subhankar Karmakar is an Associate Professor at the Centre for Environmental Science and Engineering, and an associated faculty member at the Interdisciplinary Programme in Climate Studies, IIT Bombay. He obtained his Ph.D. on "Uncertainty Modelling in Water Resources Systems" from the Indian Institute of Science, Bangalore, India, and was a Postdoctoral Fellow at the University of Western Ontario, Canada. Further, he received a BOYSCAST Fellowship from the Government of India to pursue research on Ecological Modelling at Duke University, North Carolina, USA. His primary research interests are environmental systems analysis, uncertainty modelling and risk vulnerability analysis to climate-induced natural hazards. Some of his recent research contributions include understanding the dependence of Indian summer monsoon rainfall extremes on temperature, mapping disaster vulnerability for a densely populated coastal urban area, and developing lifecycle-based decision support tools for selecting wastewater treatment alternatives. He has published over 40 international journal papers, 5 chapters and several international conference proceedings.

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Abbreviations

AAC	Autoclaved aerated concrete
AAI	Absorbing Aerosol Index
AIM	Asia-Pacific Integrated Model
AISMR	All India summer monsoon rainfall
ALOS	Advanced Land Observing Satellite
AMO	Atlantic Multidecadal Oscillation
AOD	Aerosol optical depth
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced very-high-resolution radiometer
BAU	Business as usual
BC	Black carbon
BEE	Bureau of Energy Efficiency
BLY	Bachat Lamp Yojana
BTKs	Bull's trench kilns
BUs	Billion units
CAGR	Compounded annual growth rate
CBA	Cost–benefit analysis
CCAC	Climate and Clean Air Coalition
CCS	Carbon capture and storage
CDER	Cloud droplet effective radius
CEA	Cost-effective analysis
CEEMDAN	Complete ensemble empirical mode decomposition with adaptive noise
CF	Cloud fraction
CFLs	Compact fluorescent lamps
CGE	Compound general equilibrium
CH_4	Methane
CLM	Community Land Model
CMIP	Coupled Model Intercomparison Project

CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Carbon price
CPCB	Central Pollution Control Board
CT	Carbon tax
CTP	Cloud top pressure
CTT	Cloud top temperature
CWT	Continous wavelet transform
CWV	Column water vapour
DEM	Digital Elevation Model
DRM	Dynamic recycling model
DSM	Demand-side management
EBP	Ethanol blending programme
EC	Energy conservation
ECMWF	European Centre for Medium-Range Weather Forecasts
EER	Energy efficiency ratio
EFOM	Energy Flow Optimisation Model
EMD	Empirical mode decomposition
ENSO	El Niño–Southern Oscillation
EOS	Earth Observing System
EQUINOO	Equatorial Indian Ocean Oscillation
ERB	Edmonds–Reilly–Barns model
ERFaci	Effective radiative forcing from aerosol–cloud interactions
ERFari	Effective radiative forcing from aerosol–radiation interactions
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FCBTKs	Fixed chimney Bull's trench kilns
GCAM	Global Change Assessment Model
GCMs	General circulation models
GDP	Gross domestic product
GHGs	Greenhouse gases
GoI	Government of India
GT	Gigatonne
GW	Gigawatt
GWP	Global warming potential
HCVs	Heavy commercial vehicles
HFCs	Hydrofluorocarbons
HHT	Hilbert–Huang transform
HKH	Hindu Kush Himalayan
HL	High AOD-low precipitation
HT	Hilbert transform
IAM	Integrated assessment model
IEPR	Integrated Energy Policy Report
IESM	Integrated Energy System Model
IGP	Indo-Gangetic Plains

IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IMF	Intrinsic mode decomposition
INDCs	Intended Nationally Determined Contributions
INR	Indian rupees
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ISM	Indian summer monsoon
ISMR	Indian summer monsoon rainfall
ISRO	Indian Space Research Organisation
ITCZ	Intertropical Convergence Zone
IWP	Ice water path
JJAS	June–July–August–September
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
LCHs	Light commercial vehicles
LL	Low AOD-low precipitation
LLGHGs	Long-lived greenhouse gases
LPG	Liquefied petroleum gas
LST	Longshore sediment transport
LULC	Land use/land cover
LWP	Liquid water path
MARKAL	MARKet Allocation model
MEPS	Minimum Energy Performance Standard
MISO	Monsoon intra-seasonal oscillation
MJO	Madden–Julian Oscillations
MODIS	Moderate Resolution Imaging Spectroradiometer
MOP&NG	Ministry of Petroleum and Natural Gas
MORTH	Ministry of Road Transport and Highways
MRI	Meteorological Research Institute
MT	Million tonnes
N_2O	Nitrous oxide
NAO	North Atlantic Oscillation
NAPCC	National Action Plan on Climate Change
NASA	National Aeronautics and Space Administration
NCEP	National Centre for Environmental Prediction
NCR	National Capital Region
NCT	National Capital Territory
NEMMP	National Electric Mobility Mission Plan
NEP	National Electricity Policy
NMEEE	National Mission for Enhanced Energy Efficiency
NMVOCs	Non-methane volatile organic compounds
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
O_3	Ozone
OC	Organic carbon

OMI	Ozone monitoring instrument
ONI	Oceanic Niño Index
PAT	Perform, Achieve and Trade
PBL	Planetary boundary layer
PFCs	Perfluorocarbons
Pkm	Passenger travel kilometre demand
PM	Particulate matters
$PM_{2.5}$	Particulate matter with diameter less than 2.5 μm
PRECIP	Precipitation
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
PV	Photovoltaic
QBO	Quasi-biennial oscillation
RCP	Representative Concentration Pathway
S&L	Standards and labelling
SAM	South Asian monsoon
SDB	AIM Strategic Database
SF_6	Sulphur hexafluoride
SLCPs	Short-lived climate pollutants
SMB	Surface mass balance
SO_2	Sulphur dioxide
SoV	Social vulnerability
SPOT	Satellite Pour l'Observation de la Terre
SRES	Special Report on Emission Scenarios
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
SST	Sea surface temperature
T&D	Transmission and distribution losses
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TBO	Tropospheric biennial oscillation
TDIC	Time-dependent intrinsic correlation
Tg	Teragram
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
TOMS	Total Ozone Mapping Spectrometers
UAV	Unmanned aerial vehicle
UJALA	Unnat Jyoti by Affordable LEDs for All
UNFCCC	United Nations Framework Convention on Climate Change
UVs	Utility vehicles
VSBK	Vertical shaft brick kilns
WITCH	World Induced Technological Change Model
WRF	Weather Research and Forecasting
WTP	Willingness to pay

Introduction

Climate change has emerged as one of the defining global environmental problems of this century, requiring an unprecedented global response, shaped by substantive and coordinated national responses of world nations. In early October 2016, India ratified the Paris Agreement on climate change, signalling its commitment to the "global cause of environmental protection and climate justice". At the national level, India has initiated an ambitious and sustained response through the National Action Plan on Climate Change (NAPCC), and its eight missions covering different sectors and systems. Gaps in strategic choices can create industrial and social structures that have significant adverse impact on environment and climate. India is at a critical juncture in development journey and facing choices regarding technology that could have huge long-term socio-economic and competitiveness implications. Many sectors and regions in India are highly vulnerable to climate change impacts. These include agriculture, water resources, ecosystems, as well as urban and rural settlements. Of particular importance is the fact that India is strongly exposed to the risk of a number of natural hazards of climatic and hydro-meteorological origin including, for example, extremes of temperature and rainfall perturbation.

With this background, under the auspices of the National Mission on Strategic Knowledge for Climate Change (NMSKCC) coordinated by the Department of Science and Technology through its Climate Change Programme (CCP) Division, a Centre of Excellence in Climate Studies (DST-CoECS) was established at IIT Bombay in January 2012, with a mission to "develop a scientific understanding of regional climate change and connect it to impacts (socio-economic, environment, resources) and effective response (technology and adaptation)". The core activity of the DST-CoECS is to undertake interdisciplinary, problem-driven research for end-to-end solutions addressing causes, consequences of and responses to climate change towards providing critical assessments to reduce scientific uncertainty and to support governmental decision-making on climate mitigation and adaptation measures.

In regard to India, recent influential books have addressed contemporary Indian climate politics and policy and long-term climate variability and climate change

over India using observational data and analyses. A need was thus felt to bring into focus a scientific understanding of recent climate change over India and its connection to impacts (socio-economic, environment, resources) and effective response (technology and adaptation). The objective of this book is to provide a synthesis of research findings, in terms of strategic knowledge outcomes, in regard to the emergence of recent regional climate signals, implications for impacts assessment and for mitigation and adaptation response, relevant in the Indian context. A concise interpretation is attempted to distil actionable recommendations and policy prescriptions at national and sub-national levels. The book contains 18 chapters written by the subject experts, participating in the DST-CoECS at IIT Bombay, from different academic disciplines and with distinct research expertise.

Underlying the book is a broad framework for the integration of regional climate perturbation to impacts (specifically on socio-economic sectors) and responses (adaptation and mitigation through technology response) as laid out in Fig. 1. This integration was made towards the development of a more robust response to regional climate change, to eventually contribute to mainstreaming the socio-economic context of climate change in India's development strategy. For example, linking scientific understanding and response relates to the assessment of

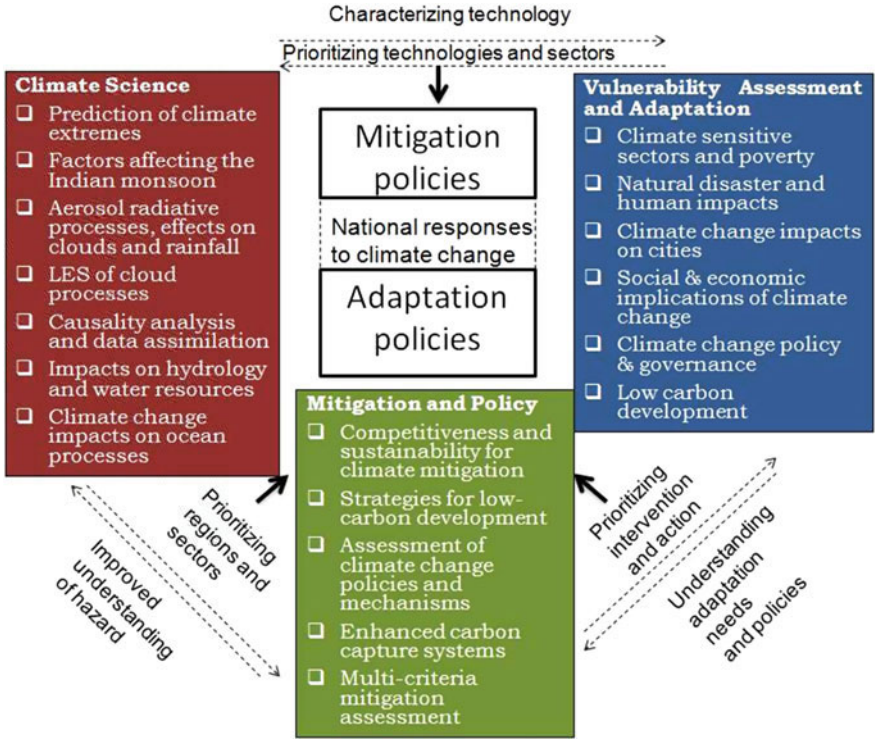

Fig. 1 Integration of understanding of regional climate perturbation, impacts and responses towards informing national policy

vulnerability and adaptation, where projections of climate and related variables (such as hydrological variables) need to be connected to impact models and used to evaluate potential adaptation responses.

Part I of the book is entitled "**Regional Climate Change Signals**".

Chapters in this part describe studies which provide evidence and scientific underpinning for the emergence of recent regional climate change signals over India and some aspects of climate response to the underlying atmosphere–ocean–land processes. Among important signals addressed are factors affecting changes in Indian monsoon rainfall and its extremes (floods and droughts), the effects of local processes and factors, like land-use changes and emission of pollution particles, on changes in summer monsoon rainfall, and hydrological scenarios, developed from the heat waves, cold waves, prolonged fog and snowfall.

Water resources are inextricably linked with climate change, and India's agricultural output, economy and societal well-being are dependent upon the stability of monsoon rainfall, its variability and its extremes. Changes in land use/land cover and direct aerosol radiative forcing significantly affect monsoon rainfall in India. This book examines the uniqueness of a computationally efficient framework, which involves an integration of global and local factors for precipitation projections through a conjugal statistical–dynamical approach and analysis based on synoptic scale fast responses acting over timescales of days to a month. Continental aerosols over India alter cloud properties in diametrically opposite ways during different monsoon years. The multidecadal gridded daily rainfall data over entire India indicates that the trend in spatial variability of mean monsoon rainfall is decreasing, on the contrary to that of extremes. There is a significant decline in the monsoon rainfall over major water surplus river basins in India. It is also revealed that the water yield in surplus river basins is decreasing but it is increasing in deficit basins.

Future projections of climate variables highlighted in the book, based on multiple climate models and scenarios for CMIP5 data, found that a sizable part of India will experience heat stress conditions in future. In northern India, the average number of days with extreme heat stress condition during the pre-monsoon hot season will reach 30. The intensification of heat waves might lead to severe heat stress and increased mortality. The information on the differential influence of various climate oscillations on ISMR at different scales is extracted and integrated into the development of improved rainfall forecasting model. From the HHT-based TDIC analysis, it is found that the strength and the nature of the association between ISMR and large-scale climatic oscillations (such as QBO, ENSO, AMO, EQINOO) vary with the timescales.

While global climate change in the long term (centuries) will be attributable to greenhouse gases, a multitude of short-lived emissions, with lifetimes of a few days to a few years, affect present-day atmosphere and climate on timescales of decades. Changes in energy consumption and development patterns will alter the regional profile of these emissions. The impacts of such changes on environmental resources will be experienced on local to regional scales, on the timescale of decades. Research which is relevant to furthering our understanding of these phenomena lies

at the interfaces between energy use, climate modelling and the estimation of impacts on multiple scales. The influence of short-lived climate pollutants, specifically aerosols, is analysed on cloud modification and short-term rainfall inhibition over India. Aerosols were shown to modulate clouds in opposing ways, suggestive of cloud inhibition in years of deficient, but invigoration in years of abundant monsoon rainfall. Enhancement in aerosol levels was linked to repeated intra-seasonal short-term suppression of daily precipitation, with increases in the frequency and length of monsoon breaks, with implications for rainfall deficit and food grain production. Linkages borne out between enhanced air pollution and short-term suppression of regional monsoon rainfall indicate the need for greater synergy in policies addressing air pollution and climate change.

Throughout the Earth's history, there have been periods of glaciation followed by warming trends, when the glaciers retreated towards higher altitudes and latitudes. The glacier ice thickness is one of the cardinal input parameters for the estimation of the total glacier volume and future glacier evolution studies. Ice thickness distribution and total glacier volume are estimated using spatially distributed GlapTop-2 model over the Chhota Shigri Glacier.

Oceans have large heat capacity; hence, ocean heat storage mainly controls the timescales of variability to changes in the ocean–atmosphere system, including the timescales of adjustment to anthropogenic radiative forcing. Energy budgets in the surface layers, which depend on the exchange with deeper layers in the ocean, indicate the need to consider the processes which affect the circulation and water mass distribution in the deep ocean. The response of the climate system at decadal and longer timescales is considered in particular. The changing climate has altered the nearshore wave characteristics and has impacted the nearshore processes like sediment transport dynamics. This may directly impact the coastal response and the economic activities along the coastal belt. Links are established between the meteorological marine climate and global dynamics with coastal processes along the Indian coastline.

As delineated in this part, the primary signals of changing climate increase in average global land and sea surface temperature and changes in characteristics of cloud cover and precipitation, along with changes in coastal and glacial ecosystems.

Part II of the book is entitled "**National and Sub-national Responses to Climate Change**".

Chapters in this part describe studies related to responses to climate change in the form of adaptation or mitigation strategies. It is essential to undertake a careful assessment of technological solutions and adaptation measures to climate change for effective planning and implementation, given limited resources available in India. There are certain socio-economic, cultural and environmental factors in the country which make it imperative for us to undertake technology assessment studies and develop capabilities/tools for the same. Such local/regional factors, ground realities and public perceptions could play an important role in making technology ranking/choice. Choices regarding these technology options need to be informed by assessments of technology characteristics, cost, performance and expected future learning. Empirical and model-based assessments are essential for this purpose.

Adaptation refers to making adjustments including those in lifestyles, technology and behaviour, in order to avoid the adverse impacts of climate change, whereas mitigation seeks to reduce greenhouse gas (GHG) and short-lived climate pollutant (SLCP) emissions, which drive climate change. As the change in climate is inevitable, adaptation is necessary for sustaining life on the planet. Mitigation is crucial to avoid future over the edge climate change scenarios which might make adaptation strategies redundant. The National Action Plan on Climate Change (NAPCC) envisages both adaptation to and mitigation of climate change.

Adaptation in marine fishing has rarely been examined in the literature and seldom receives media and policy attention. Adaptation in marginalised marine fishing communities in Maharashtra is studied, using a state-level data set inclusive of all coastal districts/villages, to understand adaptation strategies and their socio-economic determinants in the communities of concern. It is found that the community has intensified their efforts to increase yields and have also diversified into other sources of livelihood. The findings suggest the need of interventions that provide education, cooperative and financial support, through specialised credit schemes, to the community. Socio-economic attributes crucial for adaptation are identified, which can thereby assist in developing state-level adaptation programmes for the community.

The transport sector is a significant contributor of GHG emissions. Trends in GHG emission from the Indian transport sector are analysed vis-à-vis transport characteristics such as vehicle population, transport demand, fuel share and mode share. Both top-down and bottom-up methodologies are applied for GHG emission estimation. Fleet models which have been used in the Indian context to estimate the age and technology of the vehicles on road are examined. Uncertainty in CO_2 emission from different studies for Indian transport sector has been addressed and attributed to the variation in the assumptions for input variables and emission factors. Policies undertaken for the reduction in emission from the transport sector are discussed, and gaps in emission estimation study are examined.

Adoption of biofuels and energy-efficient technologies are important mitigation strategies. Two chapters of the book examine the policies promoting these mitigation strategies. Biodiesel blending in India is examined, and salient features of India's national biofuel policy are highlighted. Biodiesel blending in India received a lot of attention over the past decade. India's national biofuel policy aimed at the promotion of biofuel use made from indigenous feedstock. The current status of biodiesel blending in India is discussed, looking at the issue of economic viability. Implications are examined vis-à-vis rural development needs, complexity of the value chain and grass-roots realities. Challenges in production and commercialisation fronts to meet the country's biodiesel blending policy requirements are examined.

Further, the role of policies in realising the energy efficiency potential in India is addressed. Bottom-up techno-economic analyses of technologies in different end-uses show the presence of cost-effective energy efficiency potential. The potential of energy savings directly translates into the potential of CO_2 emission reduction. Several barriers to adoption of energy-efficient measures have been identified, and policies have been implemented to address these barriers. Some

of the important policies implemented in India include the standards and labelling (S&L) programme in appliances, and the Perform Achieve Trade (PAT) Scheme in industries and other demand-side management measures. Most of the studies report that the impact of these policies on energy and environment and the impact on consumer decisions have been largely overlooked. In this chapter, the impact of the S&L programme on both energy saving and emission reduction and on consumer decisions is presented. The cumulative emission reduction is calculated from the rate of efficiency improvements since the launch of the programme. The impact of the programme on consumer decisions is reported from a discrete choice experiment. Measures to improve the effectiveness of the programme and to enhance its contribution to energy saving and emission reduction are discussed.

The brick sector in India is of importance from its significant capacity, with an annual production of over 250 million fired bricks. The Indian brick sector is dominated by traditional kilns with inefficient combustion technology, which largely use coal, and sometimes combines with biomass and a host of other waste fuels, thus providing a unique mitigation opportunity for both GHGs and short-lived climate pollutants (SLCPs), through shifts towards more efficient technologies. Two chapters dealing with the brick sector estimate present-day emissions of SLCPs from brick production, and their evolution from 2015 to 2050, under two pathways with different levels of cleaner technology evolution, thus estimating SLCP mitigation potential. In terms of technology assessment, Bull's trench kilns contributed most to black carbon emissions while clamp kilns to emissions of organic carbon, carbon monoxide and methane. Significant achievable mitigation of SLCPs in 2050 was found possible under an ambitious prospective policies scenario, which assumes a significant shift to non-fired brick walling materials and large penetration of cleaner technologies like zigzag firing and vertical shaft brick kilns. A cost–benefit analysis shows that SLCP mitigation cost is significantly lower than those estimated for GHG mitigation in India.

Future climate action is embodied in Nationally Determined Contributions (NDCs), or national pledges to reduce emissions and undertake climate adaptation actions, given each country's unique circumstances. Under India's NDC, within a framework of common but differentiated responsibilities and respective capabilities, a broader engagement could be made, with diverse actions addressing climate change and sustainable development. While the focus of this book, on new knowledge arising from recent research in a single institution, may be seen as a modest compass of scholarship, it is hoped that its utility would lie in the synthesis of recent research findings, into strategic knowledge outcomes, relevant to policy making in the Indian context. It is envisaged that this book would serve as a reference point for understanding scientific advances and persisting uncertainty, future vulnerability and response capacity of interlinked human and natural systems, as pertaining to India.

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Part I
Regional Climate Change Signals