MEGA SCIENCE VISION - 2035
CLIMATE RESEARCH

A roadmap prepared by the
Indian Climate Research Community

Cover page: Himalayan Glaciers

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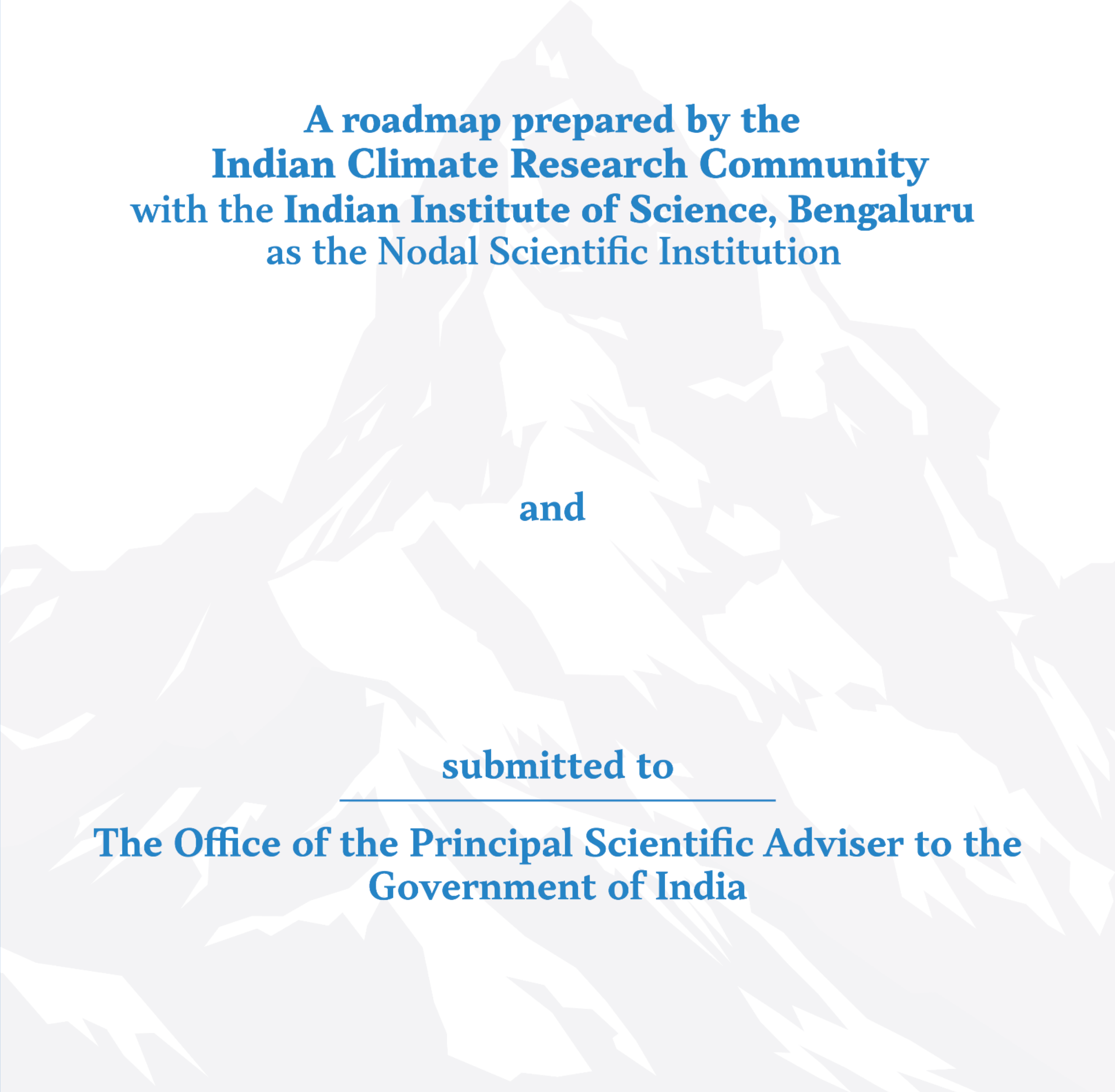

A roadmap prepared by the
Indian Climate Research Community
with the **Indian Institute of Science, Bengaluru**
as the Nodal Scientific Institution

and

submitted to

The Office of the Principal Scientific Adviser to the
Government of India

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भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

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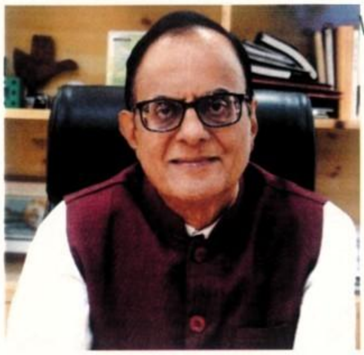

MESSAGE

Global warming-induced climate change has become a persistent challenge for humanity due to its far-reaching negative impacts on life, livelihoods, and the environment. Climate change is no longer merely a scientific issue; it now touches on critical areas such as international policy, insurance, health, economics, law and many more. Understanding climate change is vital for our country, especially in terms of water security, food security, clean air, health, economic growth, development, and maintaining a harmonious social fabric.

I am pleased to see that, after extensive consultations, the Climate Research community in India has developed a comprehensive Vision Document that addresses nearly all aspects of climate change, from understanding the science behind it to examining its effects on humans, animals, vegetation, and regional weather patterns. I am delighted to receive the **Mega Science Vision-2035 Report on Climate Research;** and I thank the Indian Institute of Science, Bengaluru, that helped us conduct this important Exercise as the Nodal Institution.

This is the first such exercise in Climate Research in the country under the Mega Science umbrella. Given that climate change affects almost every facet of life and the environment, the complexities and technological challenges in researching its science, building resilience, and developing adaptation strategies manifestly require a multi-disciplinary approach involving large-scale collaborations in experimentation, data-gathering and analyses. The Climate Research community has been following this strategy, even though it was not traditionally placed under the Mega Science umbrella. This trailblazing Exercise thus places Climate Research in its rightful place under the Mega Science umbrella. This document highlights the need for research projects that address cross-cutting themes and objectives, with collaborations across multiple ministries, organisations, institutions, industry and fields of expertise.

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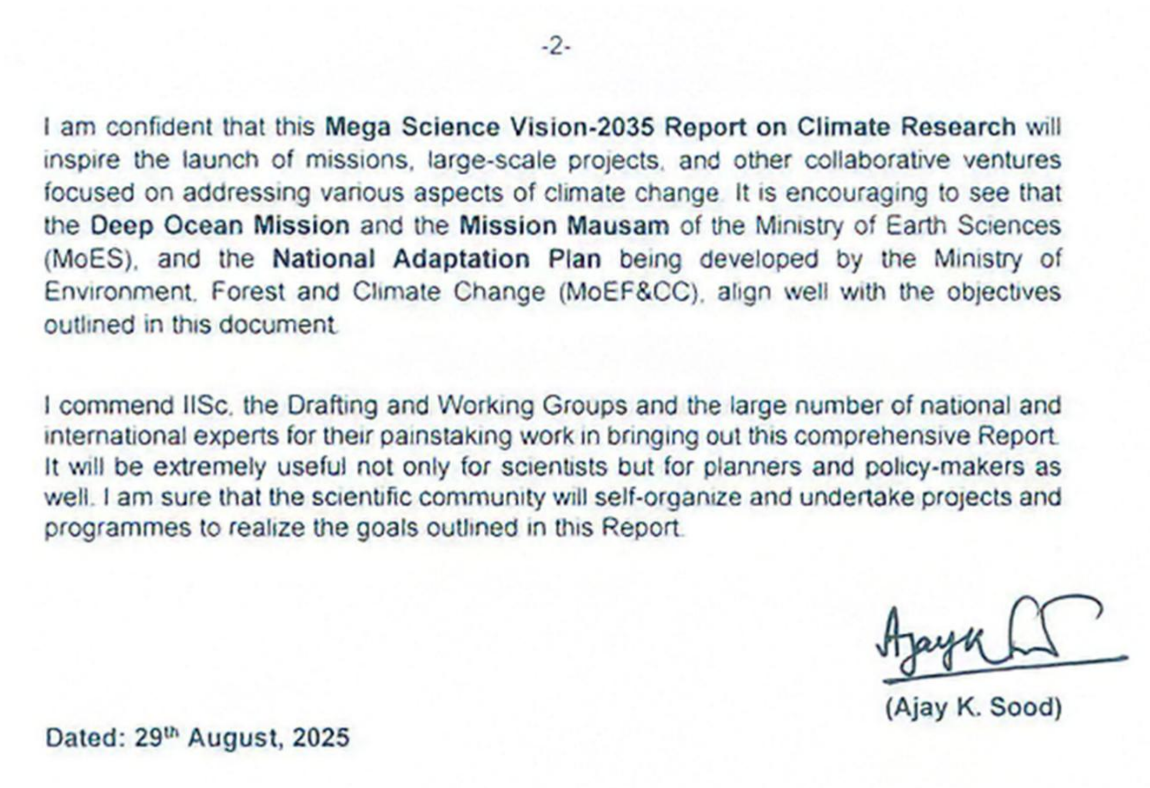

I am confident that this **Mega Science Vision-2035 Report on Climate Research** will inspire the launch of missions, large-scale projects, and other collaborative ventures focused on addressing various aspects of climate change. It is encouraging to see that the **Deep Ocean Mission** and the **Mission Mausam** of the Ministry of Earth Sciences (MoES), and the **National Adaptation Plan** being developed by the Ministry of Environment, Forest and Climate Change (MoEF&CC), align well with the objectives outlined in this document.

I commend IISc, the Drafting and Working Groups and the large number of national and international experts for their painstaking work in bringing out this comprehensive Report. It will be extremely useful not only for scientists but for planners and policy-makers as well. I am sure that the scientific community will self-organize and undertake projects and programmes to realize the goals outlined in this Report.

(Ajay K. Sood)

Dated: 29th August, 2025

सत्यमेव जयते

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Foreword

Climate Change, with its far-reaching adverse effects on our lives, livelihoods and the environment at large is a reality that is directly impacting the humankind, living and non-living resources. It is one of our greatest challenges to restrict the rate of this adverse change, and mitigate its adverse effects through effective resilience and adaptation plans. Apart from the science behind, and associated with, Climate Change, one needs to also study, *inter alia*, its ramifications for economy, health, public policies, international relations and law. The multi-dimensional implications of Climate Change necessarily make its study multi-disciplinary requiring collaboration among scientists from large number of disciplines. The science of Climate Change also requires large-scale data-gathering, analyses and modelling. Though Climate Research naturally fits into the ambit of what is called Mega Science, it missed its place under the Mega Science umbrella so far. I am happy that while facilitating the latest Mega Science Vision-2035 (MSV-2035) Exercise, our Office included Climate Research also as one of the disciplines to be covered and the MSV-2035-Climate Research Report is now being released.

This comprehensive Report first addresses the science of Climate Change in detail, before exploring its societal impacts and policy implications. Structured in six chapters, the document outlines the current status of the field, identifies gaps, and recommends the research needed to find viable solutions. Chapter 5 proposes several mega projects with a prioritized action plan. In the Annexure, the activities have been further prioritized based on two growth scenarios – Modest Growth Scenario and Aspirational Growth Scenario. Recommendations for funding and management of mega science projects have been briefly outlined in Chapter 6. Overall, the Report outlines a long-term vision for large-scale collaborative activities to further enlarge the horizons of Climate Research in the country.

We are grateful to Dr. M. Ravichandran, Secretary, Ministry of Earth Sciences, for his valuable insights into the Report. This Report would not have been possible but for the tireless work put in by the Drafting and Working Groups set up by the O/o PSA. The guidance provided by Prof. SK Satheesh as the chair of the Working Group, and the pivotal role played by Dr. SSC Shenoi as its Member-Secretary, need to be gratefully acknowledged. From the O/o PSA, Dr. Praveer Asthana, PSA Fellow, anchored this activity, provided a historical perspective of mega science vision exercises, and helped bring out the mega science facets of climate research activities. He deserves our special thanks.

I am sure, the Climate Research Community will get together and take steps to realize the vision outlined in this Report. The Report will be valuable to researchers and policy-makers dealing with societal and other aspects of climate change. This is a Vision Document out of which projects and programmes will flow; and it is encouraging that several ideas contained in this Report have been taken under some Missions recently undertaken by the Government. We expect more of this to happen in future.

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Dated: 28th August, 2025

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ABOUT THE MEGA SCIENCE VISION-2035 EXERCISE

Mega Science Projects (MSPs) are scientifically and technologically complex projects, requiring collaboration among scientists, engineers, technicians, project managers, funding organizations, industry, etc. on a large scale – occasionally from institutions and organizations in different nations across the world. MSPs, quite often, are also large in physical size and require large monetary, capital, human and intellectual resources. MSPs are also very long-term engagements – typically taking ten years for planning, another ten years for construction and, finally, remaining in operation anywhere from 20-50 years. It follows as a corollary that, at any given time, only a few such projects can be taken up nationally, or even globally.[1]

It is natural that the decision regarding which projects to launch nationally, or which projects to participate in internationally, is always taken through wide national consultations among the concerned scientific communities. This is the way it is done the world over. And, this is the way it has been done in India, at least over the past three decades. Such structured and periodic national consultations in India have been known by several names in the past. From some point of time, they have come to be known as "Vision Exercises". Since the disciplines of nuclear physics, high energy physics and accelerator science and technology and applications were the first to experience the need for MSPs, the Vision Exercises in India in the past were facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST). In the case of Astronomy & Astrophysics, the Astronomical Society of India has been periodically organizing such exercises.

In the Indian context, by 2020, a number of MSPs that had been identified in the earlier Vision Exercises had moved further towards funding and implementation. It was, therefore, felt that a time had come to carry out the next Mega Science Vision (MSV) Exercise. It was also realized that the country had travelled a long-way from the days of India-CERN Collaboration, which could aptly be called the turning point for India's engagement with MSPs. There were a number of national as well as international projects which India had nationally launched, or in which India was participating internationally. The concerned scientific communities in India had also grown more confident and ambitious about getting involved in more such projects. Also, large collaborations had become necessary in a number of other science disciplines too. It was, therefore, decided to make the MSV Exercise more structured, inclusive and comprehensive.

In consultation with DAE and DST, which had been facilitating such exercises earlier in a few disciplines, it was decided that it would be better if the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) facilitated the Exercise this time – given its pre-eminent S&T policy-making and coordination role in the GoI. The centre of activities thus got shifted to the O/o PSA to GoI. The O/o PSA to GoI decided that the Exercise this time would be carried out not only in Nuclear Physics, High Energy Physics, Astronomy & Astrophysics and Accelerator Science & Technology and Applications, but also in two additional areas, viz. Climate Research and Ecology & Environmental Science. Both these areas also require large-scale experimentation, data-gathering and analyses, and in many ways have been involved in MSPs without calling it by that name or realizing the same. The outcome of the MSV Exercise was expected to be comprehensive Roadmap Reports, one in each of the six areas. Given the typical time frame of MSPs, 2020-35 was decided as the period of focus for this MSV Exercise. Hence was born the Mega Science Vision-2035 (MSV-2035) Exercise in the six areas mentioned above.

For carrying out the MSV-2035 Exercise in Climate Research (CR), the O/o PSA to GoI requested the Indian Institute of Science (IISc), Bengaluru, to act as the Nodal Institution, to which it readily agreed. IISc also nominated Prof. SK Satheesh as the Nodal Scientist. In consultation with IISc, a Working Group (WG) was constituted with Prof. SK Satheesh as the

Chair, and Dr. SSC Shenoi, Former Director, INCOIS, Hyderabad as the Member-Secretary. A smaller sub-group of the WG acted as the Drafting Group (DG). The O/o PSA to GoI also laid down the goals of the Exercise and the methodology for national as well as international consultations during the Exercise.

The DG made exemplary effort in putting together several drafts of the document by reaching out to a large number of leading researchers in CR in the country, and after consulting similar roadmap documents from elsewhere in the world. The WG also met several times to look at the evolving drafts and offered valuable suggestions. A discussion was also organized among all the six WGs to exchange ideas about several issues that were common to all the six disciplines — for example, management structures for MSPs, aspects of fund flow, human resource development, outreach efforts, etc. Finally, a draft of the MSV-2035-CR Report got evolved which was approved by the WG for wider national consultations. Comments on the Draft Report were electronically invited from about 3200 researchers working in CR and other proximate areas in the country. Comments from 68 researchers were received and the draft was further modified in view of those comments. This draft was sent to eminent national and international experts (20-international and 15-national). An on-line meeting was organized to seek their comments, in which 19 of the experts participated. The draft was again revised in view of their comments. The draft so developed was presented before the PSA to GoI and the Scientific Secretary (SS) in the O/o PSA to GoI, prior to its submission. On their suggestion, the draft was also presented in an on-line meeting before Dr. M. Ravichandran, Secretary, Ministry of Earth Sciences. Comments and suggestions received from the PSA, SS and Dr. Ravichandran were incorporated to arrive at this final MSV-2035-CR Report.

This MSV-2035-CR Report is a "Roadmap" prepared by the national CR community outlining their hopes and aspirations for mega science activities till 2035, as best as they can foresee today. Needless to say, if there are some momentous changes in the field in this period, it might change some of the projections contained in this Report. And, a similar Exercise will again take place after another 5-6 years where this Report will get updated.

It must be emphasized that this is a 'CR community document', the preparation of which has been facilitated by the O/o PSA to GoI. Apart from putting the Report on the PSA Office website, it is planned to circulate the Report to various Ministries/Departments and Funding Agencies. It is sincerely hoped that the Report will be found useful by everyone associated with MSPs in the country in any manner. It is also hoped that the Report will be found useful by the international CR community as well.

(PRAVEER ASTHANA)
PSA Fellow, O/o PSA to GoI

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1. Asthana, P., Mega Science Programme in India – evolution and prospects, *Current Science*, 2022, **123**, 26.

Table of Contents

Executive Summary

Human activities are causing the Earth's temperature to rise rapidly, with an increase of about 0.17°C per decade. The planet has been warming since the start of the Industrial Revolution and the current period has been the warmest since the last Ice Age. No evidence suggests that these changes are natural; instead, they are driven by the buildup of greenhouse gases from industrial emissions, agriculture, livestock and other sectors. Even if all anthropogenic greenhouse gas emissions are stopped, some of these gases will remain in the atmosphere for hundreds and thousands of years.

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (IPCC, 2021), global land temperature increased by 1.590 °C during 2011-2020 compared to 1850-1900. It is unequivocal that human influence has warmed the atmosphere, ocean and land, causing widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere.

A 2000 assessment of climate over the Indian region found that the average temperature over India increased by ~ 0.7°C between 1901 and 2018, primarily due to Greenhouse Gas (GHG) induced warming. The sea surface temperature (SST) of the tropical Indian Ocean increased by 1°C on average from 1951 to 2015, exceeding the global average SST warming of 0.7°C (Roxy *et al*., 2020). The summer monsoon precipitation (June to September) over India has declined by around 6% from 1951 to 2015, with more frequent dry and wet spells during the season. Over the past six to seven decades, this reduction in monsoon rainfall has increased the likelihood of droughts in India. The sea level in the North Indian Ocean (NIO) rose at a rate of 1.06–1.75 mm per year between 1874 and 2004 (Unnikrishnan and Shankar 2007) and accelerated to 3.3 mm per year in the last two and a half decades (1993–2017) (Unnikrishnan *et al*., 2015). Although the frequency of tropical cyclones over the NIO has decreased, the number of very severe cyclonic storms (VSCSs) during the post-monsoon season has significantly increased (+1 event per decade) between 2000 and 2018.

Climate change impacts every aspect of the Earth's systems, including human health and well-being. As a result, Climate Research encompasses a broad range of issues, from understanding the science of climate change to examining its effects on humans, animals, vegetation, and regional weather patterns. Moreover, it is essential to identify the best ways to adapt to climate change. This involves developing technologies that build resilience and mitigate the adverse effects, enhancing human capacity, establishing policy frameworks, and efficiently communicating with the public and policymakers to encourage the adoption of appropriate measures to combat climate change.

This document consists of six chapters. It begins with an introduction to various aspects of climate change, followed by a detailed discussion of the science of climate change in Chapter 2. Chapter 3 highlights the broader societal impacts of climate change. Chapter 4 explores the implications of policy on society and emphasises the importance of human resource development, capacity building, and translation and communication of climate research to relevant stakeholders. Chapter 5 identifies eight Mega Science Projects with specific goals to address climate change-related issues in India. Prioritised action plans for each of these projects, along with tentative budget estimates, are also provided. Chapter 6 offers recommendations on funding and managing the Mega Science Projects on "Climate Research". Special attention has been given to identifying the lacunae/gap areas in the aspects covered in each chapter, and research needed to address those gaps is recommended. These areas of research are also briefly summarised in this Executive Summary. Coordination between Ecology and Environmental Science is crucial for successfully executing these mega science projects.

The core philosophy of this document is to provide a comprehensive overview of climate change-related sectors, covering everything from the science of climate change to its impacts on health and adaptation strategies. Since climate change impacts nearly every aspect of life and the environment, this document emphasises the need for research projects that address cross-cutting themes and objectives. Such projects would involve collaboration among multiple ministries, organisations, institutions, and fields of expertise to better understand the trajectory of climate change and its effects on lives, livelihoods, and ecosystems.

This "Vision Document" aims to inspire the launch of missions, large-scale projects, and other collaborative initiatives focusing on different aspects of climate change. The Deep Ocean Mission and Mission Mausam, currently under implementation by the Ministry of Earth Sciences (MoES) and the development of a comprehensive National Adaptation Plan to study the impacts of climate change on water resources, forestry, biodiversity, human health, agriculture and coastal ecosystems are examples of progress in this direction. While this report does not claim to be exhaustive, it represents the collective vision and aspirations of the national climate research community, based on consultations with over 3000 researchers.

1. Gap areas

Related to climate modelling and observations include:

- Inadequate observations of climate variables.
- Lack of high-resolution model simulations that can resolve the impact of topography and dynamics of extreme events for the adequate design of future infrastructure, agriculture, societal risk management and policymaking at local levels.
- Insufficient research on improving the representation of organised tropical convection, various types of precipitation systems, atmospheric boundary layer processes and aerosol-cloud microphysical processes in climate models.
- Insufficient research and observations on increasing urban heat islands and localised extreme events that cause significant damage to life and infrastructure.
- Limited field observations of glacier mass balance and depth to represent the Himalayas and validate and improve the glacier models.
- Insufficient research and observations on the impact of warming on the alpine ecosystem of the Himalaya (thermophilisation of alpine biodiversity, effect of CO_2 enrichment and warming on medicinal value of Himalayan flora, habitat shift due to shift of isotherms, shifts in onset of flowering and foliar phenological events, impact on nutrient dynamics and alpine treeline ecotone shift).

- Lack of observational datasets of soil moisture, radiation budget and other water cycle variables (evapotranspiration) at appropriate spatial and temporal resolutions.
- Lack of long-term, high-frequency data on the Indian Ocean heat and salt transport, GPS co-located tide gauges, biogeochemistry, acidification and deoxygenation.
- Lack of understanding of sources that underestimate the poleward extension of the Hadley cell in the models.
- Lack of understanding of the region's past climate based on paleoclimate proxies and their modelling to predict the future trends over South Asia.
- Inappropriate parameterisations in climate models to appropriately account for the local and regional processes.
- Inadequate understanding of India's surface and groundwater budget in a warming climate.
- Inadequate data and models to facilitate regional-scale climate projections.
- Lack of research on climate impacts on informal settlements and smaller towns.
- Little research on understanding the role of climatic variations and associated socio-economic drivers in the distribution and spread of infectious diseases and epidemics, as well as the incidence of non-communicable diseases associated with climate-related environmental risks (such as heat and particulate matter exposure).
- Inadequate integration of routine surveillance data on environmental quality with health and insufficient research on exposure-response relationships for specific health outcomes.
- Inadequate research on co-benefits for climate and health from reductions in emissions.
- Inadequate research on the design and development of clean energy, carbon capture and storage devices.

Related to capacity building, human resources, policies and communication:

- Limited trained manpower and capacity for data collection on climate variables, their analyses, standardisation, and interpretation.
- Limited trained manpower with the necessary expertise in environmental epidemiology and disease modeling to assist the health sector in climate preparedness.
- Limited capacities in public health and pollution control departments for conducting environmental health impact assessments and assessing the cost-effectiveness of climate actions, including adaptation measures.
- Lack of understanding of the long-term consequences of uncontrolled installations of large renewable energy plants on the climate.
- Lack of a framework for integrating climate change concerns with all areas of public policy and lack of clear policies to reduce emissions substantially.
- Lack of training programmes for scientists and academicians for meaningful communication of climate change-related issues with the public, policymakers, students, health workers, the medical community, local administrations and other stakeholders.
- Lack of better models for sustainable development that fuel economic growth and also protect the environment.
- Lack of scientific research to mitigate the ill effects of climate change and guide policy decisions.
- Lack of policy and planning to slow down climate change without halting economic progress.

2. Recommendations

2.1 General Recommendations:

- Continuously improve the existing climate models to better represent deep convection, cloud microphysics, aerosol interaction, thermodynamic and dynamic coupling with land surfaces, snow and sea ice and their impact on global circulation.
- Improve the existing and develop new hydrological/land surface models considering the complexity of Indian catchments and with proper representation of human interventions (e.g., irrigation, reservoir operation, and groundwater extraction). Develop new sector-specific models (e.g., for water, agriculture, and infrastructure) for impact assessment.
- Enhance the resolution of existing models and integrate them with Artificial Intelligence/Machine Learning (AI/ML) to improve future climate projections.
- Develop process-based impact models to understand the impacts of climate change on various sectors such as water, agriculture, infrastructure, public health, and others.
- Create a health-focused, inter-disciplinary, and inter-institutional eco-system that can strengthen disease surveillance/forecasting systems and develop a decision-support system to prevent and minimise health impacts from climate change, including impacts from climate disasters (such as by creating a pan-India Climate and Health Observatory).
- Evolve a seamless weather and climate prediction system integrating historical observations and improving upon existing climate models to address the science of climate change and adaptation strategy for India.
- Revisit the teleconnections using past data, including paleo, to understand various oceanic and land climate drivers on monsoons and their interactions.
- Model the conditions in the Pliocene when the CO_2 levels were comparable to the current period and verify the model results with proxy observations generated concurrently.
- Set up robust *in situ* data collection networks and space-borne SAR to continuously observe the extent and thickness of glaciers.
- Encourage modelling of the interaction between microphysical and cloud turbulence at finer scales to determine the influence of cloud feedback on climate response and uncertainties.
- Employ AI and ML to develop parameterisations for unresolved or sub-grid scale processes in models.
- Conduct primary research investigations to determine the role of the Bay of Bengal and the Arabian Sea in monsoon variations and the resultant feedback on ocean circulation, marine heatwaves and biogeochemistry.
- Generate sufficient observations on mixing in the upper layers of the Bay of Bengal and the Arabian Sea and utilise them to develop appropriate mixing schemes in the Ocean General Circulation Models.
- Develop accurate micro-scale physical parameterisations and implement them in regional climate models.

- Identify the 'capacitor regimes' in the ocean using observations and models where the oceans may ‘retain’ the influence of excessive heating and slowly release the same, thereby affecting the monsoonal weather and climate.
- Appropriately attribute the Hadley cell expansion in the models to the forcing from anthropogenic activities based on observations.
- Closely observe and model the impacts of various anthropogenic activities on climate, which cause land degradation.
- Introduce work packages related to the environment and climate change in primary education.
- Mainstream climate change education in middle, high school and college-level curricula – in science, medical science and social science.
- Strengthen S&T Education and Training for climate change by implementing R&D projects and programmes for capacity building and training of scientists, researchers, students, etc.
- Introduce a Climate Research Fellowship Programme at the Ph.D. and postdoctoral levels and in early faculty fellowships like DST Ramanujan and INSPIRE fellowships.
- Establish Global Partnerships in S&T/Social Science for Human Resource Development through bilateral and multilateral cooperation (collaborative R&D programmes, joint Ph.D./PDF programmes, exchange programmes, etc.). While doing so, lay emphasis on choosing programmes/projects required to solve the issues of local importance.
- Establish dedicated departments/divisions focused on Climate Change and Health within the School(s)/Faculty(ies) of Public Health in health science universities and strengthen human resource competencies.
- Raise climate change awareness with the participation and engagement of national and state governments, non-governmental organisations and private educational institutions.
- Encourage Public-Private Partnerships in HRD activities to develop educational tools, climate research-related skills, laboratory infrastructure, science/research parks, incubators for R&D, training centres, etc.
- Promote research to examine options for decarbonising the energy production system and other polluting systems, emitting systems, GHG producing systems (e.g., industries, transportation, etc.).
- Carry out focused research on reducing the intensity of emissions from food production and other livelihood activities specific to each community.
- Devise scientific methods to estimate the social cost of carbon (i.e., the cost of damages from an extra ton of CO_2).
- Devise a mechanism to implement the “polluter pays” principle to prevent the use of the atmosphere as a dumping ground for carbon dioxide emitted from fossil fuel use and other activities.
- Explore ways to offset the effects of the carbon tax on the poor and devise strategies for their implementation.
- Formulate plans and strategies for accelerated investment by the governments and incentivise development projects that generate employment.

- Promote research to assign an appropriate monetary value provided to the economy and factor this value into the national income accounts or GDP computation.

2.2. Recommended Mega Science Projects

(i) Strengthening the observational networks.
(ii) Indigenous development of sensors and instruments.
(iii) Remote sensing and satellite-based monitoring.
(iv) Development of indigenous India-specific climate models.
(v) Improving the existing models.
(vi) Thematic mega-campaigns/experiments.
(vii) Carbon-neutrality research.
(viii) Science of climate change adaptation and resilience (including creation of a pan-India Climate and Health Observatory).

2.3. Recommendations on funding and phased development of mega science projects

Mega science projects are typically long-term projects involving multiple institutes, large number of scientists, computational facilities, observational networks, etc. That require significant resources. A successful mega science project would need sustained funding over a long period, with proper accountability in the utilisation of funds.
We propose that:

(a) Each MSP be a pan-India collaboration with an identified project leader, with appropriate connections to international project/s, if necessary. The MSP should be approved and monitored by a high-level Apex Committee/Board co-chaired by the chiefs of all the funding agencies, with scientific experts, financial authorities, and other concerned officials of the funding agencies as members.
(b) The Apex Committee may appoint one or more high-level scientific expert committees (including a Project Evaluation Committee (PEC)) to examine and oversee the scientific and technical aspects of the project, and make appropriate recommendations to the Apex Committee.
(c) The Community Planning Exercise should be started and concluded in advance to initiate new mega projects, and a Mentor Group should be created to facilitate potential mega science projects in their early conceptual and formulation stages.
(d) Mega Science should be included in various calls given by funding agencies for bilateral/multilateral projects between India and other partner countries.
(e) Large-scale industry participation in mega science projects should be promoted and facilitated, especially for technology development.

The Working Group

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Chapter 1: Introduction

The Earth’s changing climate significantly impacts life, resources, and the environment. The Earth has warmed by at least a degree centigrade since pre-industrial times. The Sixth Assessment Report of IPCC (Assessment Report 6, AR6) states that the world's average temperature rise is likely to reach or exceed 1.5 °C between 2030 and 2050. To prevent the worst climate impacts, determined emissions cuts alone can limit the global temperature rise to 1.5 °C. The report also states that under a high-emissions scenario, the global mean temperature can rise to about 4.0 °C by 2100 with catastrophic consequences and the probability of crossing the tipping points, such as sea-level rise due to collapsing ice sheets or ocean circulation changes and the frequent occurrences of marine heat waves. The worst consequence is the irreversibility of the changes in the ocean, ice sheets, and global sea level for centuries to millennia. The IPCC 2019 Special Report on “Ocean and Cryosphere in a Changing Climate” underscores the necessity of limiting global warming to at least the level agreed to in the Paris 2015 Accord. Climate changes also affect the ability of governments to fulfil the mandates to ensure sustainable food production, water, clean air, and health and conserve species.

As agriculture and civilisations emerged, the climate settled into a relative stability period lasting over 10,000 years. Geologists call this period the Holocene. Research shows that this relative stability was expected to last another 50,000 years, but is now at risk (Ganopolski et al., 2016). Since the 1950s, the rate of change of the Earth’s climate system, in other words, the Earth's life support system, has accelerated. Extreme weather events like heat and cold waves, floods and droughts, sea-level rise, wildfires and vector-borne diseases affect the Earth’s environment and its inhabitants adversely. Some species are facing the threat of extinction in the immediate future.

The current understanding of climate science is stronger than ever. It emphasises that anthropogenic emissions, mainly from burning fossil fuels and deforestation, are responsible for climate warming and reaffirms that climate change is inevitable. To limit global warming to less than 1.5°C, it is imperative to stabilise atmospheric CO2 concentrations at around 400 ppm, a limit that has already been crossed. This uncomfortable reality has forced a new target of 450 ppm to limit the warming to 2°C or less, which is “more unlikely” than “likely”. The world is currently focusing on mitigating the effects of climate change through adaptation rather than striving to mitigate climate change itself.

The increased number, frequency and magnitude of impacts are already visible and are expected to increase further with ongoing changes in the Earth’s climate system. Much is at stake, and action is needed to reduce risks, increase resilience, and adapt to the changes. Indian science is uniquely positioned to address these complex challenges by building on its existing capacity and creating new opportunities in climate change research.

A couple of decades ago, our ability to conduct climate research and present empirical evidence based on data was limited. The ability to model the same numerically was even weaker due to factors such as limited expertise and lack of necessary computing power. However, the country has made noticeable progress during the last decade in studying various impacts of climate change on the Earth’s system, from snow-laden high mountains to deep oceans, while encompassing the lives and livelihood of the population and their health and well-being. In addition, the dependency on fossil fuels has significantly reduced owing to more affordable energy from alternative sources like solar and wind. With these capabilities, India is well-poised to take the next giant step in 'Climate Research' with a long-term vision. Such a move will provide the scientific community and the government with sufficient data and knowledge to make informed decisions and plan for the future to combat the global threat of climate change.

Climate change is not just a scientific problem anymore; it also includes several issues such as international policy, insurance, health, economics, and law. Understanding climate change is essential for our country from the perspectives of water security, food security, clean air, health, and economic growth and development. We often consider the surface temperature as a proxy to assess climate change. For India, monsoon and associated rainfall are more important than just temperature. India's extensive agriculture and economy depend significantly on monsoon rainfall. It is essential to know the quantum of monsoon rains, their temporal and spatial distribution, the timing of their onset, extreme events, etc. Even though there are no significant trends in the rainfall, the regional distribution has shown substantial variations, which is a cause for considerable concern.

Therefore, Climate Research is a multi-disciplinary field, requiring large-scale experimentation, data collection and analysis over long periods to make progress. Such large-scale, collaborative and multi-disciplinary scientific investigations naturally fit into the scope of Mega Science Projects (commonly referred to as Mega Science Programme or just Mega Science). For several decades, Mega Science Projects in India have been planned in other areas such as Nuclear Physics and High Energy Physics, through community exercises. Accordingly, such Mega Science Vision Exercises were limited to Nuclear Physics, High Energy Physics and Accelerator Science and Technology and led by the Department of Atomic Energy and the Department of Science and Technology. The last such exercise in these fields was carried out in 2014. The Astronomical Society of India carried out similar exercises in Astronomy and Astrophysics.

This time it was decided that the next Mega Science Vision-2035 (MSV-2035) Exercise would be facilitated by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI). It was also decided that the MSV-2035 Exercise would be carried out not only in Nuclear Physics, High Energy Physics (Particle Physics) and Accelerator S&T and Applications but also in Astronomy & Astrophysics, Climate Research, and Ecology & Environmental Science. Six Working Groups (WGs), one in each of these six areas, were formed to complete the MSV-2035 Exercise. The WG on Climate Research (CR) has been assigned the task of preparing a roadmap for research (especially for those needing large-scale and collaborative investigations) to fulfil the ever-increasing requirements of climate information necessary to carry out the mandate of the Government of India for sustainably maintaining natural resources, environment, clean air, water and protecting the diverse species living on land, mountains, and waters in and around India.

Research on Climate Change needs information on the past, current and future climate and the response of land, ocean, atmosphere and glaciers across relevant spatio-temporal scales. This document addresses some of the most challenging and critical objectives of Climate Change

Research in India based on the pillars of coordinated, cross-institutional actions for successful implementation.

The document is arranged into six Chapters covering most issues related to climate change and their implications. The crucial factor in understanding Climate Change is understanding the science behind the climate system and its operation. With this objective, Chapter 2 is titled Physical Science Basis. This chapter briefs on the present knowledge of climate change science, the gap areas, and the significant steps to be taken for seamless prediction of the future climate. Chapter 3 on Social Impacts of Climate Change addresses the impacts on Indian society, future impacts, mitigation, and the need for futuristic technologies, adaptation and resilience. Chapter 4 examines the policy implications, the need for human resource development/capacity building, and climate information translation and communication to decision-makers and other stakeholders. Chapter 5 proposes a few Mega Projects to be initiated and executed until 2035. The proposed projects need to involve researchers, academia, and industries and include substantial human resource development/capacity building through training programmes/workshops. These include the development of a numerical model from the first principles of climate change, covering all aspects of land-atmosphere-ocean-glaciers-sea ice, modern numerical techniques, artificial intelligence, machine learning and quantum computing technologies. The indigenous 'Self-reliant' model will also redefine and refine the physics-chemistry-biological processes and parameterisations relevant to the South Asian region that is heavily influenced by the monsoonal climate. This aspect is essential as the current numerical models are tuned initially to provide the best results for mid and high latitudes. Hence, a mega project is proposed to improve the already fine-tuned climate model further. The next mega project aims at building, launching and maintaining a series of satellites specifically targeted to generate climate quality datasets over land-atmosphere-ocean and glaciers continually to enable precise monitoring of the Earth's climate and causative factors such as the changing dynamics of the atmosphere and aerosols in the troposphere and stratosphere. A fourth mega project is proposed with similar objectives but with an extensive network of in situ measurements. A fifth mega project is defined to address targeted field campaigns that may have to be undertaken in broad collaboration with other countries and/or by the institutions in India, and the kind of national facilities to be built with an enhanced capacity to accelerate Climate Change research in the country in a big way. A sixth mega project is proposed to boost the indigenous development of sensors and instruments required to make long-term observations of climate variables. The seventh mega project has been proposed to carry out focused projects to achieve carbon neutrality by 2070. The eighth mega project aims to develop the science of climate change adaptation and resilience. Finally, Chapter 6 gives broad guidance on funding and management of Mega Science Projects on "Climate Research".

The core philosophy of this document is to provide a comprehensive overview of climate change-related sectors, encompassing everything from the science of climate change to its impact on health and adaptation strategies. In India, ministries and organisations typically focus their research on one or two specific sectors of climate change. For example, the Ministry of Earth Sciences (MoES) focuses on understanding the science behind climate change, including future projections and their impacts on weather across various time scales. Meanwhile, the Ministry of Health and Family Welfare concentrates on the effects of climate change and extreme weather events on human health, among other areas.

Since these changes and impacts stem from the same fundamental cause—climate change—this document argues for the necessity of developing and executing research projects that address cross-cutting themes and objectives. Such projects would involve collaboration between multiple ministries, organisations, institutions, and areas of expertise to better understand the trajectory of climate change and its effects on our lives, livelihoods, and surrounding ecosystems. As mentioned above, these large-scale collaborative activities thus naturally fall into the ambit of Mega Science Projects (MSPs).

It may be pointed out that this is a “Vision Document” that will inspire the launch of missions, large projects and other collaborative ventures focusing on different aspects of Climate Change. While no claim can ever be made that this Report is all-encompassing and all-inclusive, the very fact that ideas based on consultation with over 3000 researchers have been distilled in this document gives one the confidence that the Report does represent the dreams and aspirations of the community as best as possible at present.

It is thus not surprising that many of the ideas advocated in this Report have already been expressed in several Missions and Plans of the Government. The Deep Ocean Mission and Mission Mausam are already under implementation by the Ministry of Earth Sciences (MoES). Similarly, the Ministry of Environment, Forests, and Climate Change (MoEF&CC) has prepared a comprehensive National Adaptation Plan to study the impacts of climate change on water resources, forestry, biodiversity, human health, agriculture, coastal ecosystems, and more. This Vision, formulated after such widespread national and international consultations, lends further strength to these Missions, Projects and Plans. These should be seen as the flowering of the seed ideas contained in this Mega Science Vision Report. Neither this Report nor the Missions/Projects/Plans is a substitute for the other. They serve complementary purposes and have gained from each other along the way. This is only to be expected, given that the scientific communities are largely common.

As mentioned above, this document envisions guiding the development of focused, mission-mode projects with cross-cutting themes and objectives to address the issues discussed. The large-scale projects outlined in Chapter 5 are indicative; they may be integrated into the planned missions or undertaken separately, but always in a manner that complements ongoing and planned projects and missions.

Chapter 2:
Physical Science Basis

The Sixth Assessment Report of IPCC (Assessment Report 6, AR6; IPCC, 2021) states that the world's average temperature increase is likely to reach or exceed 1.5°C within the next two decades. Determined emissions cuts can only keep the global temperature rise to 1.5°C, a limit necessary to prevent the worst climate impacts. The report also states that under a high-emissions scenario, the globe may warm by about 4.0°C by 2100 with catastrophic results such as the probability of crossing the tipping points, sea-level rise due to collapsing ice sheets or ocean circulation changes. The current understanding of climate science, which is stronger than ever, emphasises that anthropogenic emissions, mainly from burning fossil fuels and deforestation, are responsible for climate warming. The IPCC-AR6 report also highlights the increasing frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, agricultural and ecological droughts in some regions, a growing proportion of intense tropical cyclones, and a reduction in Arctic Sea ice, snow cover and permafrost due to increasing global warming. Continued global warming is projected to further affect the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events. In addition, strong links have been established between extreme climatic events and human-induced warming. The worst is the irreversibility of the changes in the ocean, ice sheets and global sea level for centuries to millennia. The question before the climate scientists in India is: do we adequately understand the science that determines the effect of global/regional warming on the climatic conditions specific to our regions, like the monsoons, heat and cold waves, tropical cyclones, extreme weather, thunderstorms, dust storms, acidification and deoxygenation of oceans and the water cycle?

2.1. Observational evidence of climate change

Indian monsoon

The Indian Summer Monsoon Rainfall (ISMR), occurring from June to September (JJAS), accounts for 70% of India's annual rainfall and encompasses most of the nation except the southeastern state of Tamil Nadu. The variability of the ISMR ranges from transients through decadal timescales and beyond, mainly driven by the variability in high-frequency rain-bearing systems such as monsoon depressions, active-break cycles, long-term trends, and other drivers of monsoon variations. In recent years, tremendous improvements have been made in dynamical weather prediction, particularly in tropical cyclone track prediction, fog forecasting, extended and seasonal prediction of monsoons, owing to a quantum jump in computational capacities and improvements in modelling and data assimilation schemes. The collection of quality observational data of various states of weather and climate over the land and surrounding oceans at higher spatial and temporal resolution has vastly increased, primarily through *in situ* observatories and satellite-borne sensors. Automated sensors have strengthened the observation of oceans in recent decades. The data have shown that the temperatures are increasing, monsoon rainfall is decreasing in several regions, and the number of extreme events is increasing (Goswami *et al*. 2006). Thus, understanding the long-term trends in temperature, monsoon rainfall and extreme events has become crucial.

Greenhouse gases and aerosols modulate seasonal rainfall and the long-term trends in temperature and precipitation. Eurasian and Himalayan snow cover changes influence the monsoon at inter-annual time scales. The changes in Mascarene High, ENSO and IOD are other factors that influence the monsoon. In addition, the decadal processes such as the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO) and the 11-year solar cycle influence the monsoons. Any changes in these drivers of monsoons linked to the warming climate will surely enhance the monsoon variability and its long-term trends. Hence, future research and observational strategies need to concentrate on monitoring, understanding, and modelling monsoon variability against the background of a warming climate.

The signatures of global warming since the 1970s are also seen in the ISMR. The summer monsoon rainfall is weakening over the Gangetic Plain, Western Ghats and north-eastern regions of India, while extreme rainfall events are increasing all over India. Global warming and land-use/land-cover (LULC) intensify rainfall events. The equatorial Indian Ocean is warming faster due to anthropogenic warming. Interestingly, the land-sea temperature gradient between the sub-continent and the Indian Ocean is weakening in conjunction with the weakening of the monsoon and warming of the Indian Ocean (Bawiskar, 2009). The frequency of the monsoon depressions also weakens due to the reduction in the mid-tropospheric relative humidity. The western Bay of Bengal is warming, leading to intensified tropical cyclones, affecting the east coast and intensifying the heavy rainfall events during the northeast monsoon, especially over Tamil Nadu. Though the frequency of cyclones in the Bay of Bengal, based on historical data, is higher compared to the Arabian Sea, in recent decades, higher subsurface warming of the Arabian Sea is a matter of concern that can trigger severe cyclonic storms impacting the west coast of India.

Though there was no significant change in the total quantum of seasonal rainfall during the summer monsoon over India during the 20th century, the timing and nature of the rainfall have undergone significant changes. The frequency and intensity of extreme rainfall and drought-like conditions increased unequivocally due to the warming climate. Consequently, the frequency of flooding has increased unprecedentedly since the 1970s. It has become necessary to predict the extreme changes in rainfall patterns and their timing to plan and prepare for such eventualities that affect the day-to-day activities of citizens and food and freshwater security.

Records of terrestrial proxies and marine sediments suggest that the monsoons have been subjected to external forcings such as eccentricity-modulated precisional and solar cycles. In addition, internal forcings, such as changing CO_2 and other GHGs, dust and volcanic aerosols, inter-ocean and ocean-land temperature gradients, also influence the monsoon. Paleo-climate data suggest that the monsoon varied at different timescales, including abrupt changes linked with Dansgaard–Oeschger cycles and Heinrich events. The best analogues of the current human-induced changes are: (i) the Last Millennium (LM; ~851-1850 Common Era (CE)), (ii) Holocene (last 11.7 kilo years ago (ka)) with a focus on the mid-Holocene (~6.5ka) and (iii) Pliocene (5.33-2.58 Million years ago (Ma)).

The Last Millennium, which ended in the second half of the nineteenth century, is a close replica of the current period in terms of orbital parameters and other external forcings except for the volcanic emissions and the best observed pre-industrial climate period due to the near-unbroken and high-resolution climate data from proxies such as speleothems, tree rings and corals. During this period, several regions of India were relatively warm and wet conditions during the Medieval Climate Anomaly (MCA), also referred to as the medieval warm period (950 to 1250 CE) and the cooler and drier Little Ice Age (LIA; 1450 to 1850 CE). The proxies also indicated abrupt changes at 8.2 and 4.2 ka during the Holocene. The 8.2 ka global cooling was observed in the marine environment around India. The 4.2 ka dry event was observed in both marine and continental records. The model studies suggest the importance of changes in solar activity in modulating the mid-Holocene monsoons and multi-centennial changes in Walker circulation in modulating the ENSO-monsoon links. Solar activity in the mid-Holocene, driven primarily by changes in orbital insolation, solar output and albedo, caused considerable variability in monsoon, particularly at regional levels. However, the impact of the monsoon in the Anthropocene could stand out differently due to the changes happening faster. The rise in global CO_2 concentration since 2000 is about 20 ppm/decade, which is up to 10 times faster than any sustained rise in CO_2 during the past 800,000 years (Lüthi *et al*., 2008). Similarly, the global average temperature has been rising at a rate of 1.7°C per century since 1970, compared to a long-term decline over the past 7,000 years at a baseline rate of 0.01°C per century (Marcott *et al*., 2013).

Ocean warming, sea-level rise, and cryosphere

The latest IPCC report shows that the ocean's role in the hydrologic cycles, absorption and redistribution of anthropogenic heat and carbon dioxide, etc., has increased. About 90% of the excess anthropogenic heat goes into the oceans. Ocean warming is virtually inevitable, and there is high confidence in the rising sea level and increasing ocean acidity in the future. There is also high confidence in the shrinking of most glaciers, loss of Greenland and Antarctic ice sheets and reduction in sea ice extent in the Arctic (IPCC, 2018). Greenland lost 3900 billion tonnes of ice from 1992 to 2017, contributing approximately 11 mm to the global sea-level rise. During the same period, a loss of 2600 billion tonnes from Antarctica contributed to a 7 mm rise in the sea level. During the past 30 years, Arctic Sea ice melted at ~ 13% per decade.

Since 1993, ocean warming has doubled, from 3.22 ± 1.61 ZJ yr^{-1} to 6.28 ± 0.48 ZJ yr^{-1} in the upper 700 m. The Indian Ocean is warming at an accelerated rate (Beal *et al*., 2019). Sea surface temperature (SST) of the tropical Indian Ocean has risen by 1°C, and the upper ocean heat content has increased since the 1950s (Roxy *et al*., 2020). Increasing ocean warming will stratify the oceans vertically, inhibiting mixing between the surface and deeper waters. It was shown that the mean stratification of the upper 200 m of the global ocean increased by 2.3 ± 0.1% during 1971–1990. Increasing stratification with increasing warming would impact biological productivity and cyclonic storms. Recent work has shown that the Indian Ocean is acidifying faster than other oceans due to more significant warming. However, the storage of anthropogenic carbon in the Indian Ocean is comparable to that of other major oceans. The Indian Ocean contains one of the largest Oxygen Minimum Zones (OMZ), encompassing ~ 50% of the area (e.g. Helly and Levin 2004*)*. Studies show that in the tropical Indian Ocean, the O_2 concentration decreases rapidly because the warmer ocean water holds less oxygen and becomes buoyant, reducing the mixing of oxygenated water near the surface with deeper waters. Marine heatwaves have increased up to fourfold in the tropical Indian Ocean, aided by rapid warming in the Indian Ocean and strong El Niños, thereby impacting the monsoon by reducing the rainfall over the central Indian subcontinent while enhancing it over the southern peninsula (Saranya *et al*., 2022).

One of the significant consequences of global ocean warming and the melting of ice and glaciers is the rise in mean sea level. Regionally, this would exert considerable stress on the densely populated coastal societies along the Indian coast and low-lying island regions of the Indian Ocean. The rate of global mean sea level (GMSL) rise has increased due to human-induced climate change since 1900. Similar to the global estimates, the sea level in the Indian Ocean has risen by 1.06–1.75 mm yr^{-1} from 1874 to 2004 (Unnikrishnan and Shankar 2007) and accelerated to 3.3 mm yr^{-1} since 1993, as evident from satellite data. Indian Ocean sea-level rise is highly non-uniform and is dominated by ocean thermal expansion (IPCC AR5). Steric changes contributed to sea-level rise in the Bay of Bengal and the southeast Indian Ocean (Nidheesh *et al*., 2013).

Expansion of the tropical low-pressure belt

Since 1979, there has been a widening of the low-pressure region of the tropics, a poleward shift of the dry subtropical regions and a poleward extension of storm tracks due to the poleward expansion of Hadley circulation. This has been driven by the increasing stability in the sub-tropical high-pressure regions, suppressing baroclinic instability and leading to poleward displacement of tropical thermally driven circulation. Models and observations have given varied rates for poleward expansion of the Hadley cell, ranging between 0.1^{o} and 2^{o} latitude per decade. The observations show a much higher displacement rate than model simulations. There is a seasonal component to this shift, with the expansion occurring rapidly in the summer and fall in both hemispheres. The strongest poleward shift since 1979, exceeding 2^{o} latitude, has been observed during June-August over the northern hemisphere. This expansion of the Hadley cell has been associated with greenhouse gases, stratospheric ozone depletion during austral summer over the Southern Hemisphere and increased concentration of absorbing aerosols over the Northern Hemisphere. Additionally, natural variability can account for a significant portion of the regional trends in Hadley cell expansion: 50% of observed tropical low-pressure expansion over South and East Asia is due to the Pacific Decadal Oscillation, while globally, El Nino/La Nina has the strongest impact accounting for 20-30% of the trend.

Expansion of deserts and arid areas

Dryland covers ~ 45% of the Earth's terrestrial area and is home to more than one-third of the global population. Africa and Asia have the most extensive dryland areas, covering 15% of the global land area. India has ~ 57% of its land area under dry, sub-humid, arid, or semi-arid categories. The expansion of the Hadley cell shifts in precipitation patterns impacts the sub-tropical and mid-latitude belts. With increased global warming, drying over land is generally caused by two factors: (i) land surface warms more than the ocean on average due to more sensible heat flux over land; and (ii) water vapour over land does not increase fast enough relative to the pace of warming. These factors lead to a lower ratio between precipitation and potential evapotranspiration (P/PET) in a warming world, which is widely used to measure global aridity.

Other factors such as economic activities, population growth and land use/land cover changes pave the way for an increase in desert regions. Based on the P/PET index, the area of global drylands has increased by 4% between 1991 and 2005 compared to the 1950s. During the same period, among the different dryland categories, the observed areal increases in hyper-arid, arid, semi-arid and sub-humid land types are 0.62%, 1.16%, 2.32% and 3.32%, respectively, of the global land area. Under RCP 8.5 and 4.5 scenarios, drylands are expected to increase by 23% and 11%, respectively, with respect to the 1960-1990 baseline, with more than 70% of this expansion happening in developing countries.

2.2. Role of observations in understanding climate

Water cycle and cryosphere

Accurate monitoring and regular observations are essential for research, planning and execution of various facets of climate. Mutually complementing observational efforts through the ground and space-based platforms are to be developed to comprehensively understand the state of the land, ocean, atmosphere, cryosphere and essential elements of the integrated climate system. However, considerable uncertainty in observational parameters poses a challenge for data assimilation, cataloguing and diagnosing climate change signals/trends. Optimising the current observations, including those from different automated networks, checking the quality of data and marrying the surface observations with the remote sensing and satellite observations are necessary. Complete radar coverage will help predict lightning/thunderstorms and extreme urban extremes. Enhancements in the observational networks in India, especially the data-sparse northeast and the northwest Indian Ocean, are an immediate necessity.

Various institutions and agencies make *in situ* and satellite observations at different spatial and temporal resolutions to monitor climate variables at global and national scales. However, most of them remain part of the specific research programmes of those institutions. Indian Space Research Organisation (ISRO), through its Geosphere-Biosphere programme, has been pursuing climate research for more than three decades with studies focused on atmospheric aerosols, trace gases, GHGs, paleoclimate, land cover change, atmospheric boundary layer dynamics, carbon cycle, energy and mass exchange in the vegetative systems, ocean parameters and Regional Climate Modelling. Flux Towers equipped with state-of-the-art, high-precision instruments have been installed to measure and model the net carbon flux in vegetative ecosystems using eddy covariance techniques, satellite remote sensing data and models.

Measurements of precipitation and its variability are crucial for understanding and predicting the Earth's climate. India has the longest record (~120-140 years) of gauge rainfall at several locations. Though ground-based radar observations can provide better spatial and temporal coverage, they are plagued by significant uncertainties. Since 1871, the India Meteorological Department (IMD), through its vast network of observatories, has been measuring critical meteorological variables of temperature and wind manually at three-hour intervals and, in recent years, with automatic weather stations at hourly and sub-hourly intervals. Vertical profiles of temperature and wind are routinely measured with radiosondes. Precipitation rate has been estimated based on infrared imagery from geostationary satellites globally since the 1980s. However, this technique is indirect since visible and infrared radiance fields provide information only at the cloud-top level. The state-of-the-art precipitation radars measure the vertical distribution of precipitation, which includes invaluable information on the intensity and distribution of rain, rain type, the structure of cyclones and snow cover. Operational and research groups are now combining the available satellite, radar and gauge measurements to produce more reliable precipitation products.

It is evident from observational and modelling studies that soil moisture controls the depth and evolution of the atmospheric boundary layer (through sensible heat flux) and thereby the distribution of trace gases and their diurnal variation. Soil moisture is measured more accurately with *in situ* probes at different soil depths, but such measurements represent only a small area around the point of measurement. The space-borne soil moisture measurements are obtained from passive radiometers, scatterometers and Synthetic Aperture Radars (SARs). Retrieval of soil moisture from space sensors has a long history of almost four decades, but the recent improvements in retrieval techniques have made it possible to obtain better accuracy. ESA's Soil Moisture and Oceanic Salinity (SMOS) and NASA- JAXA's Soil Moisture Active and Passive (SMAP) are the most advanced soil moisture sensors.

Due to hostile terrain and extreme weather conditions, the distribution of the Himalayan glaciers, seasonal snow cover and possible changes in their extent are difficult to obtain using conventional field observations. The advanced remote sensing satellite-based sensors have shown that the Himalayan glaciers, except in the Karakoram region, are losing mass and retreating at varying rates since the early 20th century. The retreating Himalayan glaciers have led to the formation and expansion of glacier lakes in the past decades (Haritashya *et al*., 2018). Based on the measurements at a few locations, the increasing temperature trend over the Indian Himalayan Region is higher than the global average. The snow cover has declined since the 1960s, with an enhanced decreasing trend during the 1990s and variable trends since 2000 and is projected to decrease in the future climate as well (Krishnan *et al.*, 2020). IRS and INSAT series Indian sensors have been widely used to generate databases for snow cover and glacier maps in different spatial and temporal domains for the Indian Himalayan region. Snow, a critical climate variable, is measured globally through Earth observation data. Mountain communities may face severe water scarcity, as the small glaciers retreat in a warming climate. Improving systematic and coordinated monitoring of climate and related impacts is crucial for effective climate change adaptation and response strategies for the Indian Himalayan region.

Atmospheric aerosols

Aerosols directly affect the radiation balance of the Earth-atmosphere system by scattering and absorbing solar radiation and indirectly by modifying the cloud properties. NASA's global network of sun photometers, AERONET, measures columnar Aerosol Optical Depth (AOD), an essential climate variable. However, its coverage and presence in India are limited. The Indian network established by ISRO Aerosol Radiative Forcing over India (ARFINET) has provided long-term quality-controlled data for the last three decades. SKYNET is another international network of sun photometers with several sub-networks coordinated by the International SKYNET committee led by Japan. The India Meteorological Department is also a partner of SKYNET and shares the data from a few stations on request. Ground-based networks are also required to measure the chemical composition of aerosols and their size distribution. However, such networks are few in India and elsewhere.

Satellite remote sensing of aerosols offers the most appropriate solution for quantifying spatio-temporal variations in aerosol abundance and properties over vast geographical regions. NOAA’s Advanced Very High-Resolution Radiometer (AVHRR), NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR) and Polarisation and Directionality of Earth's Reflectances (POLDER) are important space-borne sensors for aerosol studies. Lidar remote sensing provides valuable observations of aerosols' regional/global altitude distribution. However, satellite data suffer from large uncertainties and variations due to uncertainties in the assumed surface reflectance, heterogeneity and variations in sensor performances and cloud cover. *In situ* Lidar observations are limited due to inherent complexities and expensive instrumentation. CALIPSO Lidar onboard the polar-orbiting platform provides large-scale, continuous, long-term observations, at the expense of temporal resolution and signal-to-noise ratio. High-altitude balloon flights with heavy payload capability are needed for altitude-resolved measurements of aerosol chemical species, aerosol optical properties and cloud microphysical properties, which are essential parameters for estimating direct and indirect radiative forcing due to aerosols.

The increasing CO_2 concentrations observed in recent decades are of prime concern in climate research. The mean monthly CO_2 levels have exceeded a significant milestone of 400 ppm over India in recent years, with an increasing trend of 2.15 ppm/year. Data from the space-borne Orbiting Carbon Observatory-2 is used to understand the spatio-temporal dynamics of atmospheric CO_2 (Chhabra and Gohel, 2017). Measurements made with electrochemical cells carried by small balloon ascents yield information on ozone up to ~35 km. Lidar also measures ozone profiles covering the altitude range of 10-50 km. However, a microwave radiometer can cover a wider range of 20-70 km.

Sea surface temperature and sea level

Observations of the sea level from satellite altimeters have been available since 1992 (Garcia-Soto *et al*., 2020). The findings have suggested that the sea level change trend in the oceans around India is similar to the global sea-level rise trend of ~ 3.2 mm/year. *In situ* sea level measurements are made using sea level or tide gauges, with the Mumbai gauge having the most extended data in India since 1878. Currently, 36 tide gauges are reporting data on sea level every hour. SST has increased by about 0.4ºc during the last 30 years. Satellite datasets of SST (AVHRR, 1987-2016), wind (CCMP, 1987-2016), and chlorophyll (Merged product, 1998-2016) have been used to study the long-term variability of chlorophyll-a vis-à-vis global warming. India's *in situ* observing network in the Indian Ocean consists of moored data buoys, profiling Argo floats, xbts, satellite-tracked drifters, current meters and current profiling arrays, sea-level gauges, wave rider buoys, ship-mounted AWS, etc. In addition, the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoys, Argo floats, XBT tracks, etc. deployed by other countries (USA, France, China, Japan, etc.) As part of an International programme named Indoos (Indian Ocean Observing System), also provide data on several oceanic parameters like SST, temperature and salinity, currents, CO_2, oxygen, chlorophyll, etc. Most of them provide *in situ* data in real-time mode for assimilation in the predictive ocean and atmosphere models.

2.3. Climate modelling

Dynamical models of climate

Climate models have originated from numerical weather predictions. Earth system models have evolved, enabling the investigation of past and future climate issues and leading to advances in climate modelling in recent decades. The Earth system models go beyond ocean-atmospheric coupled models by incorporating explicit representation of the carbon cycle, interactive aerosols and gases and sophisticated land surface processes. The Coupled Model Intercomparison Project (CMIP) models have convincingly demonstrated the role of anthropogenic forcing on the rising trend of global mean temperatures, but need to simulate better the impacts of climate change at regional levels. Evidence shows that anthropogenic activities have influenced the regional climate, such as increasing severe weather events and climate extremes, changing monsoon patterns and rising sea levels.

Considering these challenges, India (through the MoES) has developed an Earth System Model (IITM-ESM) by incorporating a new ocean model and several in-house developments in the ocean-atmosphere coupled weather model, Climate Forecast System-2 (CFS2) (Krishnan *et al*., 2019). The model has succeeded in simulating the mean monsoon, its variability and teleconnections and observed global warming trends commensurate with the best models worldwide. Subsequently, substantial in-house developments have been carried out to obtain a radiatively balanced global climate modelling framework appropriate for addressing the science of climate change in the Indian region. The model contributed to the recent IPCC Sixth Assessment Report 2021, for the first time from India. The observed weakening of Indian summer monsoon precipitation and projected increase by the end of the century is well represented in the model. The Indian summer monsoon teleconnection to the Indian Ocean Dipole, missing in many state-of-the-art climate models, is adequately simulated by IITM-ESM. The model needs further improvement to include interactive land-ice components and the terrestrial carbon cycle.

Paleoclimate modelling

Several coupled models confirm the findings using proxies that summer rainfall was relatively high during the Mid-Holocene (MH). The models suggest that this was due to the concurrent increase in the solar insolation associated with a shift in the ITCZ. The studies, however, differ in terms of the patterns of mean rainfall distribution. Interestingly, one model suggests that the Indian summer monsoon has not changed since MH. A few studies suggest that the monsoon-ENSO relationship was robust, though the observations suggest a weak ENSO variability during the MH. The studies also suggest that ocean feedback tempered the monsoon evolution.

The Last Millennium modelling studies that became available recently broadly support the wet monsoon during the Medieval Climate Anomaly and a dry Little Ice Age as implied by the proxy datasets. Interestingly, notwithstanding the simulated significant ENSO-monsoon links during the period, multi-centennial changes in the tropical Indo-Pacific zonal circulation and moisture availability are suggested to result in such signatures. Several other studies indicate the importance of volcanic emissions and contrasting thermodynamics of the surrounding oceans vis-à-vis the Indian landmass during the Last Millennium as important reasons. As for the Mid-Holocene, dynamical downscaling and assimilation of paleo observations may be necessary.

Modelling of clouds

Clouds remain the primary source of uncertainty in the model estimates of climate forcing, primarily due to their variability, interaction with other climate-sensitive variables and complex feedback. In recent years, significant progress has been made to realistically represent various clouds and their radiative forcing in the global and regional models. The parameterization schemes on which these models depend do not adequately represent various scales of interactions responsible for the evolution of clouds, the dependence of the evolution of clouds on physical processes and different moisture feedbacks associated with large-scale processes. Another approach is to replace the sub-grid-scale parameterisations with the (2D/3D) super-parameterisation, where the developed conceptual model provides the overall (ensemble) feedback to the global and regional models.

Recent studies have shown that the climate models, including the CMIP5 and the monsoon mission model NCEP CFSv2, show substantial biases in capturing the global low clouds, mainly due to inaccurate temperature inversion lower-tropospheric stability simulations. These studies have noted maximum biases in SW and LW radiation over the regions of persistent low clouds, mainly marine low-level clouds. These results reveal the gaps and deficiencies in the climate models in capturing the low-level clouds. Besides low-level clouds, climate models also overestimate high clouds as the convective parameterisations typically overdo the deep convection, resulting in a more substantial outflow. Due to these two significant shortcomings, the radiative balance at the top of the atmosphere in the model needs to be maintained and remains a significant challenge for climate models.

2.4 Critical gaps in climate modelling and observations

- The complexity of the climate system and feedback present a challenge to climate modelling. The present-day coarse global climate models are unable to resolve the regional processes. The climate information from the models is not adequate for designing future infrastructure, agriculture and societal risk-management strategies because of a lack of information at regional levels that include feedback on the land surface and with urban effects, lack of high-resolution simulations that can resolve the impact of topography and the dynamics of extreme events and observations that are sufficient to evaluate the skill of the models. The global climate models are inadequate for resolving coastal ocean processes for shoreline erosion and inundation studies. Due to sizeable internal variability, the projected changes in the near-term (next 10-20 years) are uncertain. The uncertainties in climate projections, especially in the near term at regional levels, pose enormous challenges for policymaking.
- Monsoon and heavy precipitation associated with lows and tropical cyclones are closely linked to how tropical cumulus convection and precipitation systems organise over large spatial scales and the exchange fluxes of heat, moisture and momentum between the atmosphere and ocean and land surface. Despite improvements in the representation of convection and precipitation processes in weather and climate models over the last several decades, the models show significant biases in simulating the organisation of tropical convective systems and the associated precipitation. Considerable research and development are required to improve the representation of organised tropical convection, types of precipitation systems (convective/stratiform) and atmospheric boundary layer processes and aerosol-cloud microphysical processes in climate models. Research on the role of planktonic dimethylsulfoniopropionate (DMSP) in cloud formation is another important aspect to be looked into.

- Due to rapid urbanisation in India, the increasing number of urban heat islands (in area and number of locations) is another factor to be studied and accounted for in weather and climate models.
- India's current skills in operational forecasts of tropical cyclone tracks are comparable to or superior to other global weather prediction centres. However, weather and climate models worldwide face significant challenges in simulating tropical cyclones and heavy precipitation over finer regional spatial scales.
- Field observations of glacier mass balance and depth are limited, and the few *in situ* mass balance measurements currently available may not represent the Himalayas (Kulkarni and Shirsat, 2019). Only 12 glaciers in the Hindukush Himalaya (HKH) have *in situ* glacier depth measurements using ground-penetrating radar. These measurements are also often performed on accessible and clean glaciers. In addition, there is a need to have more observational datasets of soil moisture, radiation budget and other water cycle variables (evapotranspiration) with appropriate spatial and temporal resolutions.
- The lack of long-term, high-frequency data on the Indian Ocean limits our understanding of the amount of heat entering and exiting the Indian Ocean through various ocean-atmospheric pathways. Thus, there is a need for continuous monitoring in the Indian Ocean through a combination of moorings, and Argo floats. Monitoring coastlines with GPS co-located tide gauges is necessary for accurate short- and long-term MSL estimates after adjusting for land subsidence/emergence. Continuous monitoring of ocean biogeochemistry is essential to understand acidification, deoxygenation and their effects on fisheries and ecosystems. Monitoring coastal circulation and hydrography and freshwater fluxes from land are required to assess coastal systems' variability and sustainable resource management. The inability to uniformly deploy and maintain *in situ* measurement platforms across the Indian Ocean is a serious concern. For example, *in situ* measurements from the western and northwestern Indian Ocean are unavailable.
- The short period over which the poleward extension of the Hadley cell has been noted from observations is inadequate to distinguish the signal of anthropogenically induced climate impacts from natural variability and other factors with high confidence. For example, changes in the Pacific Decadal Oscillation phase or the progression of stratospheric ozone depletion during the past few decades might also have played some role. Models, especially multi-model ensembles, vastly underestimate Hadley cell expansion even after accounting for the effects of absorbing aerosols and ozone. Therefore, it is crucial to understand the source of this underestimation.
- Future trends over South Asia regarding dryland areas show considerable variation and change of signs from study to study based on criteria used to delineate dryland areas. Also, the ecohydrological indicators, which have more significant uncertainties than atmospheric indicators, show a large spread in trend when different land surface models are considered. Observations of the leaf area index, widely used to indicate the arid region, have been available only since the late 1970s. Therefore, long-term trends can be challenging to verify. Uncertainties due to the internal variability of the climate system must be quantified by climate models that forecast future changes in aridity. In general, this requires large model ensembles. In addition, there is a need to understand the past changes in the monsoonal climate through paleoclimate proxies and modelling. Therefore, more paleoclimate networks need to be established.

2.5. Recommendations and future directions

- Efforts should be made to continuously improve the existing climate models by improving deep convection, cloud microphysics, aerosol interaction, thermodynamic and dynamic coupling with land surfaces, snow and sea ice and their impact on the global circulation. Due to inadequate model resolution, current-generation models cannot assimilate large amounts of crucial and available observational information. The spatial resolution of the models should improve by at least up to 12 km. Transition to a full Earth-system modelling capability in India needs to be achieved to deliver a wider breadth of information-rich data consistent across the atmosphere, land, ocean, sea ice and hydrological elements and provide reliable projections of future climate over the Indian region. Integrating the same with advanced technologies like AI/ML would improve future climate projections. Regional-scale water management and soil and vegetation restoration are essential to check the expansion of desert regions. Land use/land cover changes leading to desertification are primarily associated with water bodies. In addition, there is a strong need to develop process-based impact models to understand the impacts of climate change on various sectors, including water, agriculture, infrastructure, public health and others.
- Seamless weather and climate prediction systems need to be evolved by integrating historical observations and improving upon existing climate models to address the science of climate change and adaptation strategy for India. Models that can simulate and document the past climate can also be expected to simulate future climate reasonably well. It would be helpful to revisit the teleconnections using past climate data to understand various oceanic and land climate drivers on monsoons and their interactions. There is a need to model the era in Pliocene when the CO2 levels were comparable to the current period to generate analogues of future climate verifiable with proxy observations. Concerted use of targeted proxy observations and model experiments would help unravel the potential role of abrupt climate shifts that may have led to droughts and, therefore, the collapse of agriculture and civilisations. Such close interaction between paleo-observational and paleo-modelling communities helps reduce the gaps in understanding the past climate and identify efficient analogues of current and future climate variability/change and teleconnections.
- As far as glaciers are concerned, models estimating mass balance and thickness need validation with *in situ* observations. Therefore, robust *in situ* data collection is necessary for improving the present models. In addition, statistical downscaling of the coarser-resolution climate projections through a comparison with observational features and statistics may provide a benchmark for future impacts and feedback on glaciers. Meteorological data is needed in modelling to estimate mass balance and runoff. Further, snow cover can be retrieved easily from satellite datasets, but snow depth is difficult to obtain. It is important that the space-borne SAR continuously monitor the accumulation/melt of snow and ice. Thus, greater efforts are needed to continuously monitor and develop snow depth maps at large spatial scales.
- Modelling the interaction between microphysical and cloud turbulence at finer scales is an emerging research area for constraining the processes (e.g. entrainment in cumulus clouds) that influence cloud feedback, climate response and climate modelling uncertainties. AI (in contemporary usage, deep-neural networks) and ML can be used to develop parameterizations for unresolved or sub-grid scale processes, downscaling ESM outputs to

finer scales and construct forecasting time series. However, all these applications are still in their infancy. Hybrid forecasting (using AI + knowledge-based models) is also in its infancy in forecasting the nonlinear time series. However, the application of the hybrid technique for climate prediction appears promising.

- The role of the Bay of Bengal and the Arabian Sea in monsoon variations and the resultant feedback on ocean circulation and biogeochemistry need primary research intervention. Oceans typically interact with the atmosphere through SST. The present-day models have either cold or warm biases in SST over many ocean regions, including the Bay of Bengal. The recent observations suggest that the freshwater layer over the Bay of Bengal creates a unique situation that is different from the mixing processes envisaged in the Ocean General Circulation Models. More observations are required to develop new mixing schemes in the ocean models to address such issues. Similarly, the available limited observations suggest large deviations in the air-sea exchange fluxes estimated by the models using bulk parameterizations based on the limited observations from the Pacific Ocean. Direct observations of air-sea fluxes and their parameterization in the coupled models must address these issues.
- It has been suggested that the recent warming of the Indian Ocean has impacted the monsoon significantly. The oceans warm and cool slowly and release heat to the atmosphere slowly like a 'capacitor'. Hence, it is imperative to identify the 'capacitor regimes' that may 'retain' the influence of various ocean drivers and pass it to the monsoons next summer or modulate extreme weather events. The role of ocean interactions with monsoons needs more scrutiny. The recent warming in the Bay of Bengal has been suggested to exacerbate the northeast monsoon and extreme rainfall events.
- Appropriate formulations in models are required to attribute the Hadley cell expansion to the forcing from anthropogenic activities, such as emissions of greenhouse gases and black carbon and absorbing aerosols. Observations must be made to understand the effects of stratospheric ozone depletion and its reduction by controlling ozone-depleting substances. Another requirement is to model and understand the impact of Hadley cell expansion on the hydrological cycle.
- Regional-scale water management and soil and vegetation restoration are essential to check the expansion of desert regions. Land use/land cover changes leading to desertification are primarily associated with disappearing water bodies. Much of the degraded soil is related to intense agricultural activities and irrigation, which initially leads to increased agricultural production and ultimately results in land degradation. Close observations and modelling to understand the impacts of various anthropogenic and climatic activities on land degradation leading to desertification are required for long-term planning of water management, agriculture and other land use/land cover activities of economic and ecological importance.

Chapter 3: Societal Impacts of Climate Change

3.1. Projections of future impacts of climate change: Indian scenario

Under different climate change scenarios, future climate projections over the Indian region indicate robust changes in the mean and extremes of several key climatic parameters. The IPCC AR6 has assessed that the global mean surface temperature would continue to rise over the 21st century with increasing GHGs. Multi-model projections based on CMIP6 models indicate an increase in the surface temperature over the Indian region between 2.3°C and 5.3°C by the end of the 21st century (with the mean projected increase of about 4.4°C relative to the recent past (1976-2005 average) under RCP8.5). The warming pattern exhibits distinct seasonality and spatiality, with higher warming projected over North India and more significant warming during the pre-monsoon season. Under the high emission scenario, the frequencies of occurrence of warm days and warm nights are projected to increase by 55% and 75%, respectively. The frequency of summer heatwaves over India is projected to be 3 to 4 times relative to 1976-2005 by the end of the 21st century (Mukherjee and Mishra, 2018). Heat stress is expected to amplify over India in response to the combined rise in surface temperature and humidity.

In line with the projected global mean precipitation (1-3% per degree increase in global surface temperature), the climate models project an increase in the annual and summer monsoon (June-September) precipitation over the Indian region. Summer monsoon precipitation is projected to increase by 0.33 mm/day and 0.84 mm/day over the Indian region under medium and high emission scenarios, respectively, by the end of the 21st century. Moreover, the interannual variability of summer monsoon rainfall is also projected to increase over India through the 21st century. The frequency of extreme precipitation events is also projected to increase during the 21st century (Turner and Slingo, 2009). One–Five-day precipitation maxima at a 5–500 year return period would increase by 10–30% under a high emission scenario. The frequency of extreme precipitation is projected to rise more prominently over southern and central India by the middle and end of the 21st century.

During the 21st century, the global ocean is projected to have higher temperatures, greater upper ocean stratification, acidification, oxygen decline and alteration of net primary production. As the Indian Ocean is tropical, landlocked in the north without heat exchange with the northern polar regions, its rate of warming is the fastest. The SST is projected to increase by 2.7°C in the tropical Indian Ocean by the 21st century. Projected changes in SST in the Indian Ocean show regional differences and seasonal variability. In the north Indian Ocean, the Arabian Sea is projected to warm more than the Bay of Bengal. Higher warming is projected over the northwestern equatorial Indian Ocean and lesser warming over the southeast, with the Indian Ocean mean state resembling a positive Indian Ocean Dipole (IOD) pattern. With warming, positive IOD events are projected to increase, which is favourable for above-normal summer monsoon rainfall over India. The increasing stratification with increasing warming in the Indian Ocean can impact corals' biological productivity and life, leading to severe cyclonic events. With the increase in ocean warming, marine heatwave events are projected to occur frequently over tropical oceans, including the Indian Ocean region. The five primary drivers of marine ecosystem change (surface warming, acidification, oxygen loss, nitrate content and net primary production change) are projected to increase globally by 60% by the end of the 21st century under a high emission scenario (IPCC SROCC).

The increase in temperature and changes in salinity, known as steric sea level rise, mainly contribute to the rise in mean sea level in the Indian Ocean. At the same time, mass addition from melting glaciers is also a major contributor to global mean sea-level rise. The steric sea level in the Indian Ocean is projected to increase by about 20–30 cm by the end of the 21st century. With the increase in the mean sea level, frequent storm surges are projected at many locations by 2050 under all scenarios, especially in tropical regions (SROCC, IPCC). The increasing frequency of high water levels can severely impact coastal areas, depending on exposure. In addition, sea-level rise also affects coastal populations in various ways, including inundation, flood and storm damage, erosion, saltwater intrusion, rising water tables and impeded drainage, wetland loss, causing severe hardships in terms of livelihood and habitat loss.

3.2. Key gaps

- **Improvements in models and parameterisations**: The impacts of climate change are evident from local to regional scales; however, processes at these scales need to be better represented in global climate models. Future projections of the South Asian monsoon rainfall based on the CMIP models exhibit a wide range of variations and uncertainties. The CMIP6 models disagree even on the sign of projected precipitation change over monsoon regions, including the Indian region. In addition, critical physical processes such as convection parameterisation and ocean mixing that are relevant to the Indian region are not well represented in the climate models. Even the considerably finer model resolutions, made possible by exascale computing, do not avert the need for parameterisation in the Earth System models. Cloud microphysics and turbulence (with a Kolmogorov scale as small as a millimetre), surface processes and processes arising from biology/evolution must continue to be parameterised. Parameterisation continues to give rise to Earth System modelling uncertainty (structural, owing to multiple choices of the equations and closures of the unresolved processes, and parametric, owing to numerous options for the parameters of these equations). Uncertainty in estimating the steady climate state leads to a continued need for initial condition ensembles for these ESMs.
- **Surface and groundwater budget**: Projected changes in mean and extreme climate affect India's surface and groundwater storage variability. For instance, low-intensity precipitation favours the monsoon season groundwater recharge in North India, whereas high-intensity rainfall is more beneficial for groundwater recharge in South India. The role of projected change in precipitation on integrated surface and groundwater systems needs to be critically examined in India. Given the uncertainty in the projected rainfall,

approaches based on sensitivity analysis are required to understand the changes in surface and groundwater resources in a warming climate in India.

- **Regional-scale climate projections:** Efforts are needed to develop the regional-scale climate projections for climate change impact assessment in India. Projected surface and groundwater storage changes depend on the changes in the irrigated areas and irrigation demands, irrigation methods, irrigation efficiency and cropping patterns. Groundwater component representation in global climate models (GCMs) needs to be improved by including complex interactions between humans and the climate, and providing proper representation of land cover change and water withdrawals.
- **Validation of, and improvements in, glacier models and meteorological data generation**: To understand the changes over the high mountain regions and projected changes in glaciers in a warming climate, models estimating mass balance and thickness need to be validated with *in situ* data. Therefore, robust *in situ* data collection is necessary to improve the present models. Systematic efforts are required for continuous mass balance measurements to generate reliable long-term mass balance time series of benchmark glaciers. The scarcity of meteorological data needed to model and estimate mass balance and runoff (due to the shortage of meteorological stations in the HKH) adds uncertainty to the simulations.
- **Urban planning**: Despite the critical positioning of cities in the Indian climate scenario, several gaps exist in practice and research. While cities are essential players in Indian climate interventions, many cities lack official mandates to develop climate action plans and do not integrate climate adaptation with their comprehensive development plans. There is a gap in research on climate impacts in informal settlements and smaller towns.
- **Epidemics and lack of understanding of the role of climate change:** In terms of disease management, very little research has been conducted in understanding the role of climatic variations and associated socio-economic drivers in the distribution and spread of infectious diseases and epidemics. Data from 1990 to 2016 are available at the National Health Profile, Government of India. The number of communicable diseases decreased from 61 to 33% and non-communicable diseases increased from 30 to 55%. Given the influence of factors such as human migration on the movement of diseases across the country, there is a need to reassess the idea of endemism in infectious disease research. Further, given the anticipated increase in ambient temperature and worsening air/water quality, changes in patterns of physical activity and nutritional shifts, there is a need to strengthen the understanding of non-communicable disease epidemiology stemming from modifiable environmental risk factors.
- **Health sector preparedness for climate emergencies:** Climate change is expected to cause unexpected and unprecedented pressures on the health systems, especially within vulnerable populations, including the urban poor and remote rural communities. The primary healthcare workforce and departments of public health already bear an enormous burden of providing access to preventive, reproductive, maternal, child and infectious/vector-borne disease-related services. Extreme disruptions in these services induced by climate emergencies and disasters can cause extraordinary setbacks to the public health gains made in the last decades. The health sector capacities have to be strengthened via technical, administrative and infrastructure investments to address changing patterns of climate change-induced environmental impacts.

- **Clean energy**: Climate change mitigation requires increased energy efficiency and transformation to clean energy sources, which requires carbon capture and storage technologies at a significant scale. A grid with higher renewables share will require system-level modelling to ensure the grid's stability and supply. Reducing the cost of grid-scale battery storage technologies, new technologies in long-term energy storage and new policies and paradigms for flexible load management are needed to sustain a 100% renewable grid. Nuclear power and tiny modular nuclear reactors have a role to play as a steady non-fossil energy source. Significant work is required to design, develop and deploy these reactors. New renewable energy forms from the ocean, air and the earth's heat are yet to be understood for technical and commercial viability. Their implementation must be taken up, thereby aiding carbon neutrality. Cement is the single largest source of CO_2 from the industry/materials sector. Decarbonising the cement sector involves efficiency improvement, clinker and fuel substitution and CO_2 capture and storage. Technological advancements in traditional building methods and new building materials like cross-laminated timber that can one day replace cement are equally important.
- **Carbon capture and storage**: Sub-surface carbon storage and sequestration sites, their characteristics and capacity need to be estimated for the Indian subcontinent. Carbon capture and utilisation technologies in power, fertiliser, food processing and other industries have to be developed and deployed at scale. The matching of sources and sinks of CO_2 at the global scale has to be modelled.

3.3. Societal impacts

Climate change has significantly impacted society both directly and through its impact on natural ecosystems. Extreme weather events like heatwaves, floods and extreme rainfall have significantly impacted biodiversity and agriculture, people's livelihoods and wealth, and social resilience and well-being. Measuring these impacts and understanding the causal relationships between climate change and extreme weather will lead to further research on responses and policies required to reduce these adverse impacts.

Agriculture and fisheries

Since agriculture has a high sensitivity to temperatures and precipitation and a strong dependence of the population on it, it is one of the sectors most impacted by climate change. The significant climatic impacts on agriculture are linked to three climatic factors: (i) *increasing temperature*, (ii) *dry and wet extremes in rainfall distribution*, and (iii) *rising sea level*s. The projected increase in temperature can lead to carbon dioxide fertilisation. However, there has been a reduction in the net primary productivity globally after the 2000s due to increased aridity and drought, limiting photosynthesis. Yield losses of up to 36% for wheat and 20% for rice have been estimated in India due to the combined effects of ozone and heat (Burney and Ramanathan,2014). Other studies have found that warming has reduced wheat yields by 5.2% between 1981 and 2009, despite adaptation, including irrigation. More specifically, under various future climate change scenarios, an aggregate decline of 2.3% and 8.62% is projected in food grain production (including rice, wheat, pulses and coarse cereals) in ten major food-producing states in India in 2030 and 2050, respectively.

Apart from impacts on the yield, climate change due to an increasing concentration of atmospheric CO_2 also lowers the concentration of zinc and other micro-nutrients in essential food crops, thereby exacerbating substantial global health problems due to dietary deficiencies of zinc and iron (FAO 2013). It has been projected that about 48 million people residing in India alone will be affected by zinc deficiency by 2050 (Myers *et al.* 2015). Climate change is also predicted to lead to boundary changes in areas suitable for growing certain crops in India. In India, subsistence fisheries provide substantial animal protein in people's diets. Water quality deterioration in deltas and other wetland fisheries affects inland fishery production. As a major inland fisheries producer, India may lose a large share of its production. Salinity ingressions will further compound this. Warming of marine waters, acidification and deoxygenation affect marine fisheries.

Water resources

Water security has multiple dimensions: water for drinking, water for sanitation and hygiene, water for food production, water for economic activities, ecosystems and water use for cultural purposes. Water security risks are associated with water-related hazards such as drought, floods, poor water quality, water contamination and related health issues. Water scarcity may result in conflicts between users, damage to livelihood, hinder socio-economic development and reduce overall human well-being. For instance, inadequate water supply can lead to long-term health impacts such as child stunting.

The summer monsoon rainfall and Himalayan glacier melts are India’s primary drivers of streamflow and reservoir storage. Therefore, the variability of summer monsoon precipitation affects the availability of surface water in the Indian river basins. Also, the year-to-year precipitation variability is projected to increase in the future warming climate, posing more challenges to India's water resources. Climate change is also projected to alter the timing of snowmelt and extent of snow cover, severely affecting the Himalayan River basins and the projected reduction in streamflow. Due to the increase in population, urbanisation, irrigation demands and precipitation variability, India's rapid groundwater depletion is a critical concern that directly impacts millions. Rapid groundwater depletion, changing rainfall characteristics, skewed distribution of water availability and increasing water demands pose enormous pressure on water security under India's climate change scenario.

India is home to 18% of the global human population and 15% of the global livestock population, which is over only 2% of the landmass and 4% of global freshwater resources. With the rapid population growth and industrialisation in the recent century, water demand has increased enormously. In contrast, the per capita water availability is projected to decline from 1588 $m^3\ yr^{-1}$ to 1140 $m^3\ yr^{-1}$ by 2050 due to climate change (Konapala *et al*., 2020). About 80% of the annual precipitation occurs during the summer monsoon season (June-September), which is projected to behave erratically with increasing events of floods and droughts. The demand for water for irrigation, industry and domestic use is expected to grow by 30-40% by 2050 from the 2010 level, whereas the drought severity is projected to increase in the future, posing severe challenges to food and water security in India. The frequency of extreme precipitation has increased three-fold in the past few decades, accelerating floods in India. The changing monsoon pattern has substantially affected the water availability in the Indian river basins. Climate change also significantly alters the water cycle, affecting the critical components, including precipitation, evapotranspiration and runoff.

As the world's largest user of groundwater, India has 20 million wells and tube wells. It uses 250 km^3 of groundwater annually (Mukherji and Singh, 2020), which is almost 20% of the total groundwater extracted globally (Aeschbach-Hertig and Gleeson, 2012). In the last 40 years, intensive groundwater use in India has brought tremendous socioeconomic benefits by buffering against rainfall variability, ensuring food security, providing livelihood support and alleviating rural poverty. However, since the over-exploitation of groundwater in India has already impacted agricultural benefits, cropping intensity may fall in the coming years.

The global glacier retreat has been unprecedented since 1850, and glaciers are projected to lose mass under future warming. Himalayan glaciers are sensitive to climatic conditions and have been retreating since the mid-19th century. Glaciers, except for those in the Karakoram region, are losing mass and retreating at varying rates since the early 20th century. The Hindu Kush Himalayas (HKH) has seen an increased temperature over 4-5 decades. Several areas of the HKH have shown a decline in snowfall and retreat of glaciers in recent decades. With continued warming, future changes in temperature and precipitation are expected to alter the sensitive cryospheric processes over the HKH. By the end of the 21st century, the annual mean surface temperature over the HKH is projected to increase by 5.2°C along with increased annual precipitation under high emission scenarios. Globally, in many high mountain areas, the stability of slopes is projected to decrease further owing to glacier retreat and permafrost thaw. Also, floods due to glacier lake outbursts or rain-on-snow, landslides and snow avalanches are projected at new locations in the 21st century.

Natural hazards and resulting disasters

India is prone to many natural hazards, including compound hazards like the 2013 Uttarakhand flood and landslides arising from extreme precipitation and glacial lake outbursts along the Mandakini river. Melting of the cryosphere causes hazards such as glacial lake formations and their outbursts, leading to sudden floods, as in the Sutlej River in the Indus basin during 2000 and 2005.

There has been a threefold increase in widespread extreme rain events in central India from 1950 to 2015, leading to flooding and influencing land degradation. The return rate and severity of floods in South Asia are projected to increase under all rcps (except RCP 2.6) (IPCC, 2018). The number of people exposed to 1-in-100-year storm surge events is one of the highest in India due to increased exposure of the coastal population. Extreme heavy rainfall, cloud bursts and landslides/mudslides are projected to increase, causing irreparable damage to the infrastructure in the hilly terrains. Similarly, droughts caused by hot and dry extremes are projected to increase under the warming climate in India.

Indian cities are already vulnerable to heatwaves and associated thermal discomfort. A study conducted in seven urban centres situated on the west coast of India over 46 years has shown a significant increase in thermal discomfort experienced since the 1990s. There has been an increase in relative humidity in Indian cities between 1974 and 2004, and an increase in hot days across the west coast of India. Cities like Kozhikode and Panaji are most vulnerable in this context. These vulnerabilities are exacerbated by the effects of urbanisation, such as the prevalence of day and night-time urban heat island effects. In landlocked cities, the impact of urban heat islands becomes virtually inseparable from climate change. An increase in middle to upper-income households is likely to result in more investment in energy-intensive cooling devices, especially air conditioners, thus raising the urban climate footprint.

Indian cities are highly vulnerable to conditions of drought brought on by the interplay of urbanisation-related water stress and climate change. Over 30 Indian cities will face elevated water risks by 2050 (WWF, 2020). By 2050, Jaipur may face the second-highest global water deficit, with Chennai ranked 20th globally. Over 31% of urban India lives in slums and informal settlements without access to piped or public tap water (NITI Aayog, 2018). There is evidence of urban drought in cities such as Chennai, Bengaluru, Delhi, Kanpur, Bhubaneswar, Jodhpur and Indore, causing both tangible (economic) and intangible (conflict) adverse impacts.

Urban floods are increasingly becoming commonplace in India. Coastal towns and cities such as Chennai and Mumbai face threats of sea-level rise, exacerbated by bad urban planning and the reclamation of lakes and natural drainage networks. The nexus between climate change vulnerabilities and uneven urbanisation impacts urban residents, with vulnerable populations bearing the maximum effect.

India is among the top ten countries expected to be highly exposed to the risk of sea-level rise under a 1.5°C temperature rise above the present level, primarily due to a dense coastal population. The SLR leads to increased flooding during storm surges, tsunamis and coastal erosion. As many megacities are coastal (e.g. Mumbai, Chennai, Kolkata), sea-level rise poses a high risk for the urban population and infrastructure. The sea-level rise also accelerates shoreline erosion and the quantity of sediment delivered to the coastal regions. Further, groundwater salinity in the coastal areas can rise due to sea-level change, impacting the availability of drinking water to the coastal inhabitants. Though a lot is known regarding the sea-level rise, risks on the areal extent, resources, and the affected population are yet to be assessed.

Ecosystems and energy

The ecosystem-related impacts taking place at present are projected to intensify in the future. For example, in the Darjeeling district, a significant change in lichen community structure has been documented in response to climate change and anthropogenic pressures. Events of coral reef bleaching on the southeast coast of India due to anomalous sea surface temperatures have increased. Increased sea surface temperature, elevated carbon dioxide concentration and consequent decrease in oxygen are likely to affect marine ecosystems. For instance, increased drought frequency causes increased evaporation in the estuaries, thus increasing salinity. On the other hand, increased precipitation under the warming climate can result in frequent floods, which transfer large amounts of pesticides and nutrients, facilitating more significant phytoplankton growth in the river mouths. Also, coastal storms and the increased frequency of cyclones can cause more frequent inundations of low-lying areas.

Roughly half of the Indian forests are highly vulnerable to climate change in both the short and long term under RCP 4.5 and 8.5. Forests in the Western Himalayas (e.g., Himachal Pradesh) are shown to be vulnerable to global warming under both RCP 4.5 and RCP 8.4 in the short-run (2021-2050) and long-run (2070-2099). The rising temperature has led to the extinction of several species of flora and fauna. An increase in wildfire incidents due to global warming is projected to reduce the range of certain critical tree species endemic to the Indian Himalayas. The increase in wildfires reduces long-term water flow, changes soil moisture and affects water quality through higher sedimentation. Due to developmental projects, the fragmentation of forest areas has affected the survival of several wild species and resulted in significant changes in their population and distribution. Significant alterations in the phenology of organisms, including migration and breeding cycles, are being observed. Though greening trends have increased globally and in India in the last 20-30 years by over 1/5th to 1/3rd, mainly due to land use management and expansion in croplands, the increase in forest cover has been minimal. On the other hand, reduced precipitation has affected species diversity in tropical forests. The rise in invasive species is another major challenge. The warming climate has pushed treeline elevation further in the Himalayan regions, reducing the highest elevation zones and expanding tropical and subtropical zones.

Climate change also affects the energy sector through temperature changes and precipitation regimes. This impact is felt more in hydroelectric plants. India is projected to increase hydropower production from 5% to 25% by the mid to end of the 21st century. Due to increased temperature and precipitation, hydropower production is projected to decline in hydropower plants located on snow-dominated rivers.

Public health

Climate change has become a critical challenge in today's rapidly urbanising world, particularly in Indian cities and has considerable implications for public health. India has over 50 urban agglomerations with a population exceeding a million inhabitants, and an urban population of over 400 million. This number is expected to double by 2050 (GoI, 2011). India's rapid urbanisation coincides with a rising global engagement with the perils of climate change. Thus, the country is poised to make the first large-scale climate-conscious urban transition (Khosla and Bhardwaj, 2018). While urban shifts in India are already challenged by rapid population growth, industrialisation and associated land-use change, these issues are exacerbated by vulnerabilities created due to a changing climate.

Urban centres across the country face various climate challenges that include thermal discomfort, increased extreme events such as floods and drought, and unpredictable timing of rainfall. Climate change also exacerbates existing urban vulnerabilities such as air pollution, loss or degradation of urban green spaces, water stress and the spread of infectious diseases. Climate change disproportionately affects the marginalised sections and the urban poor who rely on the informal sector for their livelihood. The urban population in India is projected to grow by 35 per cent (UNDESA, 2018) by 2050. Given the fast pace of urbanisation in India, the impacts of climate change are being felt in urban areas and are likely to exacerbate in the future. Intense heatwaves for longer durations that occur more often are projected for India (Murari et al., 2015).

The transmission of vector-borne diseases (VBDs) like dengue and malaria is linked to climate and weather variables. Climate change has caused changes in VBDs such as dengue, malaria, chikungunya, Nipah and Kyasnur Forest disease. The global dengue incidences and transmission rate in India have increased since the 1950s due to climate factors (temperature, relative humidity and rainfall) and non-climatic factors (urbanisation, global air travel and ineffective vector control measures). Urban climate influences the spread of infections through mechanisms affecting the geographic spread and disease transmission of modes by vectors. Climate-related changes in temperature and humidity affect the distribution of disease vectors such as rodents, fleas, ticks and parasites. Indirect effects of climate change, such as human migration and land-use change, further shape the patterns and occurrence of such diseases by influencing vector reservoirs' movements and the fragmentation of urban landscapes. Climate change is also likely to impact a large population living in villages.

High temperatures and extreme heat events have also been linked to a higher risk of mortality and morbidity, post-traumatic stress disorder and anxiety. Recent studies have reported that spikes in average summer temperature and the number of extremely hot days caused by climate change are projected to cause more than 1.5 million deaths annually in India (Carleton *et al.,* 2022). Another significant health impact on the respiratory system is caused by increased air pollution levels in India. According to projections, premature mortality due to PM2.5 in India would increase by 2.4–4% during 2031-2040 and 28.5–38.8% during 2091–2100 under RCP8.5. Urban air pollution is a massive challenge for Indian cities, with Delhi, Agra, Kolkata, and Mumbai consistently recording abnormally poor air quality values over the past decade. Air quality deficits are linked to various health disorders. In addition to well-known urban causes of air pollution, such as the transport and energy sector, studies have further demonstrated that peri-urban crop residue burning and the use of solid cook fuels by rural communities are significant contributors to ambient PM 2.5 across rural and urban areas in multiple states (Chatterjee *et al.,* 2023).

Finally, climate change is expected to have major health impacts on women and children in India, with the poor likely to be affected most severely. With increasing malnutrition and related health disorders, child stunting, for example, is projected to increase by 35% by 2050 compared to a scenario without climate change (Dimitrova*,* 2022; WEF Report 2024). The United Nations Framework Convention on Climate Change notes that women face higher risks and experience a greater burden of climate change impacts. Climate change impacts on health, including increased exposure to heat, poor air quality, extreme weather events, and altered vector-borne disease transmission, reduced water quality, and decreased food security, affect men and women differently due to biological, socioeconomic, and cultural factors. In India, where rapid environmental changes are taking place, climate change threatens to widen existing gender-based health disparities, making climate change a major risk multiplier (Sorenson*,* 2018).

3.4. Adaptation and resilience

The challenges posed by climate change across sectors are widely acknowledged. Adapting to climate change and developing resilience to mitigate the adverse impacts are crucial, especially for developing economies like India. Adaptation encompasses all measures to reduce the adverse effects of climate change by adjusting to the expected changes in climate. A compelling adaptation mechanism should exploit the available opportunities to reduce climate change impacts on the people and the economy. In addition to adaptive measures, there is a need to develop resilience to climate change. Resilience makes sectors and communities resistant to the adverse impacts of climate change and ensures their proper functioning. Geographic, socio-economic and demographic distribution make India particularly vulnerable to climate change vagaries.

Adaptation actions include the tasks undertaken to reduce the risk or impact of climate change (IPCC AR5, 2014). For instance, green roofs are installed to lessen the impact of urban heating. Moreover, adaptation actions can include those focused on reducing a specific risk, such as designing a building against flooding or cultivating less water-intensive crops in water-scarce regions. Adaptation actions can also include recent updates or adjustments in the traditional practices, such as non-stationarity assumption (in the place of stationarity) in flood risk assessment, moving agricultural regions or crops to new areas and with shifting climate. Also, the success of adaptation action in any sector can depend on activities in other sectors. Adaptation processes commonly start with risk assessment, impacts and vulnerabilities, then move to a plan for the adaptation and implementation of adaptation measures, and finally to the monitoring and evaluation stage. Based on previous experiences, the assessment of adaptation efforts must be carried out effectively. It must focus on how adaptation measures are developed, designed and implemented (process and governance), and how much such measures contribute to the well-being of people by reducing climate change impacts, risks, and vulnerability, and improving resilience (IPCC AR5, 2014).

Needs for adaptation and resilience

The adaptation efforts in the country need to be further improved by making available greater financial resources, adequate knowledge of climate change impact on vulnerable populations, more effective policies and ensuring effective implementation. Adaptive measures such as constructing barriers and embankments require significant investments and may not be robust enough for future extremes. Community-level adaptation strategies, such as increasing awareness and access to climate education and technology, would strengthen resilience against long-term impacts. There is a need for combinations of short-term and long-term policies to mitigate projected climate damages. Nature-based adaptation solutions that focus predominantly on rejuvenating forest resources have multiple benefits: conservation of water resources, soil conservation, sustainable development of forest communities, improving food security by providing alternative food choices and sustaining wild flora and fauna. There is a need to move from reactive adaptation practices to proactive techniques that reduce greenhouse gas emissions and limit future warming.

Proper planning and implementation of adaptation measures need observations, projections, and historical data. Therefore, data is necessary for adaptation at different spatial and temporal scales. Observational datasets used for the adaptation process include gauge station data of hydrological components, atmosphere, land, and ocean observations. Observed datasets and future projections are used to understand the climate processes and their risks and impacts at all scales. Hence, there is a need to strengthen climate-relevant observational networks to understand climate change impacts at appropriate spatial and temporal resolutions and plan and implement adaptive measures at the local, regional and global levels. Since high-resolution climate projections are essential for proactive adaptation planning, high-resolution climate modelling efforts must be strengthened in the coming decades. Climate data information can be improved further by focusing on three significant aspects:

- *Exploiting the big data from space-based observations and innovative solutions like machine learning and cloud and edge computing.*
- *Ensuring open access to all existing data, including rescuing of historical data and lifting restrictive data policies.*
- *Closing remaining data gaps through long-term funding of in situ observational systems and innovative ways of providing interdisciplinary data and information for local adaptation and decision-making.*

Transformational adaptation strategies, including large-scale interventions such as dams and water transfer infrastructure, room for rivers, reclamation of lakes, etc. are required to avoid water scarcity. Early warning systems for hydro-climatic extremes are needed to reduce the impact of climate change and assist in water management. Moreover, adaptation mechanisms such as wetland restoration, change in irrigation patterns from flood irrigation to drip irrigation, change in cropping patterns and awareness of rainwater harvesting and water conservation are needed. Besides climate change, human activities such as groundwater extraction, groundwater contamination and surface water pollution affect water availability. Adaptation strategies such as watershed management, construction of small check dams for groundwater recharge, construction of ponds at the local level, groundwater regulation, preservation of aquifers, wastewater-treatment plants and waste management guidelines are required.

To improve food production in the changing climate, it is necessary to plan properly and adapt to the planting and harvesting time and cultivate new crops with modern irrigation techniques. Conventional approaches, genetics and genomics strategies can be used to develop stress-resistant cultivars. To ensure food security and sustainable livelihood of the rural population, there is a need to frame policies that could support the small and marginal farmers by strengthening their capacity to fight climate change impacts through maximum insurance cover, provisions for timely procurement of crops, distribution of climate-resistant seeds at a reasonable cost, and extension of employment guarantee programmes.

In the fisheries sector, proper early warning systems, seasonal bans on trawling during breeding seasons, policies that aid small-scale fisheries, protection of breeding and nursery grounds and providing ample alternative livelihood options would help build climate resilience. The sentiments of the indigenous fishing communities could be positively reaped for community-based sustainable fisheries management (FAO, 2012). In addition to the existing adaptation strategies, innovative measures to enhance current and future adaptations should include an emphasis on enabling policies that include security of land tenure, ensuring timely availability of low-cost credit, investments in critical infrastructure like irrigation and transportation systems, addressing poverty and the gender gaps and bridging the lack of technological access (IPCC SRCCL, 2019).

As the impact on coastal zones differs from region to region, the adaptation strategies should be region-specific and address the specific climatic driver that causes a significant effect on a particular area. The efforts should begin by identifying vulnerable zones and the primary climatic factor driving the vulnerability. Considerable efforts are required to restore dead coral reefs, control fishing and dangerous practices like trolling, where fish wealth is disproportionately affected and prevent invasive species. Early warning systems need to be developed to reduce the impacts caused by cyclonic storms. Conservation and rejuvenation of mangrove forests would help mitigate the effects of storm surges and improve the livelihood of coastal inhabitants. Also, proper efforts should be made to prevent algal growth by reducing marine pollution and implementing restrictions to prevent the overuse of pesticides. Measures to protect the coastal wetlands and maintenance of water quality should be adopted to withstand rising sea levels. Policy level changes that mandate proper zoning measures in the coastal areas are inevitable to avoid construction in vulnerable zones. Effective measures are required to reduce marine pollution by ships and container vessels and restrict the removal of beach sediments. Active restoration of coastal habitats like coral reefs and mangroves can increase fish wealth; however, the long-term sustainability of coral reefs needs to be guaranteed.

Technologies like deploying artificial reefs for coastal fishing reduce the pressure on coral reefs and seagrass fishing, discouraging destructive bottom trawl fishing. Culturing larval forms of commercially important fish and prawn species in aquaculture farms and sea ranching in the coastal waters improves the capture fishery. Research on the technologies of cage culture, macroalgal and molluscan cultures, which will support the livelihood of artisanal fishermen, could effectively address the issues of adaptation and mitigation.

Globally, attempts to develop heat-tolerant corals resistant to bleaching are being experimented with. Introducing salt-tolerant crops could reduce the impacts on agriculture due to seawater ingress in the coastal areas. As daily consumption of saline water can cause serious health issues, groundwater desalination becomes necessary. Community-level water-treatment plants could be adopted to provide livelihood options and address water salinity. Also, check dams, bunds and recharge reservoirs can be constructed to prevent salinity ingress. Further, investments in climate-resilient coastal highways, housing and power infrastructure are crucial to building coastal communities' resilience against the impact of disasters.

Significant interventions are required to reduce climate change impacts on forest ecosystems. Continuous monitoring of wild species can help identify vulnerable species. Further steps should be taken to relocate vulnerable species to favourable habitats. Preserving and protecting vulnerable species in artificial environments can help fight the extinction of species to a large extent. There is a need to establish a fast and effective fire-response system that considers local knowledge to reduce the impact of forest fires. Migration pathways must be created for the safe movement of animals, and proper measures must be taken to reduce human-animal conflicts. Artificial implantation of indigenous species and artificial insemination could be adopted to reduce the problem of invasive species. Steps need to be taken to relocate affected populations, especially in areas where annual flooding is expected.

The forest sector also provides ample opportunities to mitigate climate change. Interventions such as urban forestry, sustainable forestry and management of protected areas with due consideration to the conservation of biodiversity, soil and water would reduce the impacts on the forest ecosystem and mitigate climate change by increasing carbon sequestration. Different strategies are adopted globally to reduce the risk of forest degradation and ensure forest ecosystem services. They include: (i) establishment of 'neonative' forests, which include intermixing non-native species that withstand climate change impact along with native species, (ii) a combination of reactive and active adaptation strategies to conserve forest resources, (iii) robust adaptation strategies considering a wide range of uncertainty in projections for possible scenarios, (iv) several adoption strategies that include water management, soil conservation, crop diversification and construction practices for the indigenous communities living in protected areas to reduce the impacts on forests and conserve resources.

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Chapter 4:

Policy Implications, Human Resource and Capacity Development and Translation/Communication

4.1. Human resource and capacity development

Human resource in Science and Technology is a significant driver for India's emergence as a knowledge and economic superpower. Strategic and sustained support with higher investments in Science and Technology education and training in schools, colleges, universities, research institutions and industries is essential in generating a competent scientific workforce. India's gross expenditure on research and development is about 0.7% of its GDP, which is relatively modest. It is also equally essential to improve the quality and novelty of research to be at par with other leading countries in scientific R&D. Industries in India must commercialise the research outcomes that emerge from the scientific community. A robust ecosystem promoting research and development in the country to attain self-sufficiency in all walks of life, including climate change research, is necessary for realising the vision of "*Atmanirbhar Bharat*".

Addressing climate change requires a multidisciplinary approach that links natural and social sciences, policymakers, experts and non-experts, and traditional scientific knowledge. Challenges and discrepancies exist not only in the projections of climate change and physical elements of adaptation design but also in understanding the human dimensions of the consequences of climate change and identifying preferred means of adaptation for diverse stakeholders. Each stakeholder group's capacity needs to be enhanced to successfully address the above issues.

4.2. Gap areas in capacity building

In 2019, the Paris Committee on capacity-building conducted an assessment identifying specific gaps and needs in agriculture, coastal zone management, disaster risk reduction, energy, health, infrastructure, and water resources. The committee also identified mitigation strategies in agriculture, energy, forestry, transport and waste and concluded as:

- There are capacity gaps and needs regarding the generation, collection, analysis, and standardisation of quality data related to climate change adaptation and mitigation. The lack of quality observations and projections hinders the creation of a robust knowledge base for determining appropriate and targeted adaptation and mitigation actions.
- Capacity gaps exist in generating or collecting data on GHG, particularly the emissions from the forestry, energy and transport sectors.
- Lack of capacity for the appropriate analysis of data on climate-related impacts. It is necessary to develop and interpret the climate scenarios and make informed decisions about climate risks, vulnerability, and resilience.

4.3. Recommendations and way forward

Key Initiatives proposed for Human Resources Development and capacity-building activities include:

(i) Introduction of work packages related to the environment and climate change in primary education.
(ii) Mainstreaming climate change education in the middle and high school curricula (CBSE, ICSE and State Boards) – in science and social science, since there is currently very little climate change material in the school curriculum.
(iii) Strengthening Science and Technology Education and Training for climate change by implementing R&D projects and programmes for capacity building and training scientists, researchers, and students. Mainstreaming climate change education into professional curricula in medicine, engineering, architecture, economics, business administration and other large-scale areas of national focus where climate awareness is essential for building climate resilience.
(iv) Climate Research Fellowship Programmes at the PhD and postdoctoral levels, and an early faculty fellowship like DST Ramanujan and INSPIRE fellowships.
(v) Global Partnerships in S&T/Social Science for Human Resource Development through bilateral and multilateral cooperation via collaborative R&D programmes, joint PhD/PDF programmes, and exchange programmes, while emphasising indigenous capacity development and identification of S&T programmes to solve the issues of local importance.
(vi) Establishing dedicated departments/divisions focused on Climate Change and Health within Schools/Faculties of Public Health in health science universities and strengthening human resource competencies.
(vii) Raising climate change awareness, participation, and engagement at various levels by increasing the involvement of national governmental and non-governmental organisations and private educational institutions in capacity-building activities.

4.4. Policy and translation/communication

The Intergovernmental Panel on Climate Change (IPCC) consolidated climate change-related research through interdisciplinary approaches in the first assessment report. The panel is now slowly shifting its focus to solutions for climate change impacts. Addressing the challenges posed by climate change requires the generation of knowledge involving natural, technological, social and indigenous information and the ability to analyse it to enable decision-making and communication with the user community.

Effective communication of climate change information is essential to develop workable, cost-effective and sustainable solutions, leading to improved living standards while adapting to climate change. Communicating climate science to make the message more relevant to non-scientific stakeholders is also crucial.

Establishing partnerships among scientists, policymakers, decision-makers, and practitioners is necessary. Scientists and academicians must work with social scientists and communication experts to appropriately communicate scientific knowledge to society so that the community is motivated and empowered to adopt solutions to address the impacts of climate change.

Appropriate technical guidelines and frameworks need to be developed regarding production of climate change related knowledge, its communication and its application in formulating adaptation strategies and plans.

4.5. Gap areas/need for effective policy intervention on climate change

Climate Change has created a niche in environmental policy issues. In addition to the impact on ecological systems, climate change has become one of the most pressing international development issues. Anthropogenic warming threatens, among other things, to alter the spatial distribution of infectious and respiratory diseases, increase weather-related mortality, increase the salinity and temperature of oceans, modify the supply, demand and quality of freshwater, radically alter crop yields and the area of arable land and increase the frequency and severity of natural hazards.

Various policies proposed to address potentially anthropogenic climate change include limits on carbon dioxide emissions from oil, coal and natural gas as well as support for renewable energy production, such as wind and solar energy. Since the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), there has been a marked increase in national policies and legislation on climate change-related issues. However, these policies have yet to succeed in achieving a substantial reduction in emissions.

Though renewable energy seems to be the right solution to replace polluting energy sources, studies are needed to understand the long-term consequences of the uncontrolled tapping of natural resources. Popular policies for addressing climate change are switchovers to renewable energy and increased energy efficiency. Moderately favoured policies include carbon pricing, carbon taxation and carbon sequestration. The National Action Plan on Climate Change, launched by India in 2008, serves as a roadmap to combat climate change without compromising the country’s developmental concerns and economic growth.

Climate change concerns need to be integrated with all areas of public policy, particularly economic and social policies. This will require addressing possible conflicts and defining trade-offs between policy objectives and potential "co-benefits". The co-benefits of GHG mitigation actions include improved energy security, urban air quality and human health benefits.

Climate change-informed policies, programmes, and projects focus on reducing greenhouse gas emissions or creating the necessary conditions for people and social institutions to adapt to climate variability and risks, making societies more resilient to existing or future impacts of climate change.

Mainstreaming climate change adaptation into all relevant areas of public policy is a priority. However, there is limited knowledge and understanding of the impacts of climate change policies and their mainstreaming into developmental policies. Hence, there arises an immediate need for effective policy intervention on Climate Change with a deeper understanding of relationships between climate change-related interventions and issues of poverty, exclusion and inequality in other relevant policy domains (e.g. energy, water, agriculture, forestry, urban planning).

4.6. Thrust areas

Climate change communication is about educating, informing, warning, persuading, mobilising, and solving this critical problem. Connecting with the audience based on shared values builds trust between the communicator and the audience. The following are some recommendations for communicating meaningfully with the public, policymakers, and other stakeholders.

Communicating with the public

It is essential to use language that makes climate science relatable to the concerned community, like connecting with their socio-cultural values and local interests. This requires knowledge about their likely interests and requirements. Using anecdotes and stories rather than statistics and graphs would be helpful and practical.

Communicating with policymakers

A partnership between climate change science and policy must be forged at multiple levels to be effective. Many organisations are developing programmes to increase the relevance of their science and data products for decision-makers. Climate change policy and decision-making happen at various levels – from local government to international negotiations through the United Nations Framework Convention on Climate Change. The outcomes should have societal impact and relevance and be financially feasible. Awareness programmes for legislators on important issues related to Climate Change relevant to policy and society (water policy, air quality and health, renewable energy, agriculture, etc.) would be desirable. In addition, policy briefs on topics of interest to governments should convey the complex science in simple terms, avoiding technical jargon so that the non-specialists can also understand and appreciate the issues well.

Communicating with young researchers/ students

Exposure to climate change science should start early at the primary level of education. Equipping the school labs for students to perform experiments on the impact of climate change can engender their interest in this field. A climate science/change awareness programme for the benefit of high school students should contain, but not be limited to, lectures on climate science/change issues related to the environment by eminent scientists, a demonstration of methods for measuring climate-relevant parameters, a climate science quiz contest and so on. Science Briefs should utilise cartoons and simple language to describe the issues to school students.

Climate-economics nexus: critical gaps

- Climate change is one of the biggest challenges of this century that requires increased efficiency of energy usage and transition of energy and material selection to non-fossil alternatives. It also requires carbon capture and storage technologies on a significant scale.
- Economic development in the industrial era has caused climate change. Economic development constrained by climate change is a challenge. Pathways for such development do not exist, and new paradigms are required.
- Economic paradigms that can help couple degrowth in highly developed countries with economic growth in less developed countries need to be explored. Behavioural change can significantly impact energy consumption patterns, but is difficult to model. Economic models that consider human behaviour, shifts and nudge factors can provide better mitigation strategies. A few models properly capture the catastrophic impacts of sudden climate change on the long-term economy.
- While climate change needs to be mitigated, development is also critical for society. The Intergovernmental Panel on Climate Change report clearly states that we are already facing the consequences of 1-degree warming, such as extreme weather events, sea-level rise, glacier melting, and so on. Fresh scientific evidence only reaffirms that climate change is inevitable. To limit global warming to less than 1.5°C, we would need to stabilise greenhouse gas concentrations to around 400 ppm, though the concentrations have already crossed the mark.
- We should aim for adaptation through sustainable development. Sustainable growth calls for the intelligent utilisation of technological advancements for development with minimal impact on climate and ecosystems. Energy transitions take a long time to reflect the structural changes in the economy. Reducing economic growth is not a viable pathway to achieving climate goals.

Sustainable development that accounts for economic growth and protects the environment

Economic development and environmental sustainability need not be mutually exclusive. In India, many people live below the poverty line, and hence, continued economic growth and development are critical. There is no easy way to decouple economic growth from emissions. Though we are far from reaching a steady-state economy with a constant growth rate, we must pay special attention to reducing disparities in income and welfare while marching towards that goal. Hence, better models for sustainable development that fuel economic growth and protect the environment by assigning appropriate monetary incentives/value for actions are necessary.

Scientific research to mitigate the ill effects of climate change and guide policy

The ill effects of climate change include extreme weather events, biodiversity loss, sea-level rise, health issues, and epidemic disease. Research should provide a scientific basis for governments to develop climate-related policies. For example, the low-carbon transition has environmental "co-benefits", including improved air quality, biodiversity conservation and preservation of forests. Economic models tend to ignore such co-benefits. It is equally vital that scientific research also pays attention to local and regional problems to help sensitise policymakers at all levels, national, state and district levels, about the consequences of the projected impacts in their long-term planning.

Policy and planning perspective to slow climate change without halting economic progress

Though India's per capita emission is much lower than developed countries, India is considered to be the world's third-largest emitter as its energy system is heavily fossil-dominated. Hence, we must contribute to emission reductions. The Indian government has already committed to decarbonising the energy sector and reducing the emissions intensity (of the economy) by 33% by 2030. A significant carbon tax is one option to reduce emissions. The last five years have seen dramatic growth in the rise of renewable energy's share in our energy mix, especially in electricity generation. The shift toward increased electrification of transport and other applications will also impact the primary energy mix. Renewable energy should be given priority so that the momentum gained in the last five years is not lost. Policy support can increase grid resilience and flexibility to accommodate further expansion of renewables and provide incentives to state electricity boards. Together, the government investment in this sector needs to be further ramped up.

4.7. Recommendations and future directions

1. Research should examine options for decarbonising the energy production system and other systems (e.g., industries, transportation, etc.) that release GHGs as part of the chemical process.
2. Focused research is needed to reduce the emission intensity of food production and other livelihood activities specific to each community.
3. Scientific estimation of the social cost of carbon (i.e., cost of damages from an extra ton of CO_2).
4. Explore ways to offset the effects of the carbon tax on the poor and devise strategies for implementation.
5. Formulate plans and strategies for government investment during the prevalence of low borrowing costs and incentivise the development projects aimed at employment generation.
6. Promote research to assign an appropriate monetary value to the ecosystem and environmental services provided to the economy and factor this value into the national income accounts or GDP computation.
7. Promote research to find solutions for the management of already affected populations.
8. Devise a mechanism to implement the "polluter pays" principle to prevent the use of the atmosphere as a dumping ground for carbon dioxide emitted from fossil fuel use and other activities.

Chapter 5: Mega Science Projects for Climate Research

Recognizing the fact that the climate is changing, the most critical inputs needed for sustainability and policy-making under the changing climate are: (i) an assessment of the impact of climate variability and climate change on the society directly and indirectly through perturbations of the environmental constituents (weather, water, air, and so on) and (ii) realistic prediction of the future scenario with the lowest ambiguity. These call for (a) the generation of an accurate and realistic database over the region, on land-ocean-atmosphere and other environmental variables critical to climate (essential climate variables, ecvs) with good temporal and spatial resolution, (b) the development and proliferation of essential scientific instruments by enabling close involvement of scientific institutions, academia and industries, (c) development of India-specific state-of-the-art indigenous models to simulate the climate impacts, (d) conceiving and conducting mega-field campaigns aimed at enhancing the knowledge to mitigate the impacts of climate change, (e) carrying out focused research on technology to achieve carbon neutrality and (f) studying the science of climate change adaptation and resilience.

Keeping this in focus, the following Mega Science projects are proposed to better understand the climate, and its impact on society, and generate the knowledge required to formulate a national policy.

5.1. Observational networks

The fundamental requirement for climate change studies is the generation of long-term high accuracy data on (i) the essential climate forcing agents such as greenhouse gases, anthropogenic trace gases, ocean heat content, scattering and absorbing aerosols, etc. on one hand and (ii) the essential weather and environmental parameters that have a direct bearing on the sustainability of life and biosphere (such as temperature, rainfall, cloud cover, snow and glacier cover, oxygenation and acidification of oceans) on the other. While the former form the essential inputs to the models that are needed to assess the changes in the concentration of species affecting the climate directly and indirectly, the latter are needed for validating the models and improving them by incorporating better dynamics and assessing the impact of climate change on the biosphere.

There have been numerous studies on climate variability and climate change, globally and over India. Many of these have direct or indirect implications on the policy (national and international). Some of those studies have drawn contrasting inferences over Indian regions (especially on the monsoon, crop yield, snow cover and temperature) owing to a lack of accurate and long-term (decadal scale and above) data on climate forcing agents at adequate spatial and temporal resolutions to represent the enormous diversity of Indian region and the large number of unrealistic or regionally irrelevant assumptions used in the models to fill the gaps. Different studies have used different databases/different properties to prescribe climate forcing agents, partly due to the unavailability of adequate data. Such studies, not relevant or validated in the Indian region, tend to adopt data generated elsewhere (for example, emission inventory) under different environments (for example, temperate zones) to fill the data gaps in the model inputs. Several studies have even used chemistry transport model output as input for the models. In some cases, satellite data (with known uncertainties, especially over heterogeneous landmasses) have been used as input for climate models due to a lack of data with better regional representation. While satellite data are adequate for uniformly mixed gases such as GHGs, they are highly uncertain with respect to aerosols, surface albedo, and ground reaching radiation and are deduced using models validated elsewhere. Surprisingly, most of these studies have yet to utilise measured aerosol properties (even to the limited extent of availability) over India. One reason is the non-availability of gridded data of the parameters relevant to climate. This necessitates the generation, careful validation and archival of data required for climate simulations within our country. That will greatly help generate realistic regional impact information to deal with the policy matters and international negotiations. Several nations, including the USA, the European Union nations, and China, have already established a national database for their regions and are expanding with a global focus. Any delay in addressing this issue will push India to the wall soon and make us dependent on what others have to say about the future scenario in our region.

Even if we use the same inputs in different models, the results could be different due to various parameterisation schemes, grid resolution, initial conditions, unrealistic simulation of regional meteorology and so on. This scenario is further complicated by studies that use different models and input datasets. Often, the inferences from most of these studies are questionable. However, to challenge the inferences from such studies, the availability of quality data for our region is a prerequisite. Also, considering the implications of such questionable inferences on future climate projections, policy-making and society, it is essential to have a national network of climate observatories with well-defined objectives.

Realising this need, in the recent past, certain national institutions (such as ISRO), departments (DST) and ministries (MoES) have set up their networks for research purposes. But they remain as independent entities without standard measurement/calibration/instrument/analysis protocols and spatio-temporal coverage. Each network also has its focus and objectives, measuring different atmospheric or land parameters of interest to the institutions concerned. Hence, a comprehensive network to generate high-quality datasets on the essential climate variables over the Indian region and the surrounding ocean is required for Earth System Models and Satellite data validations. The primary requirements of climate quality datasets are accuracy, stability and sustainability (longer duration) and near-homogeneous sub-regional representation. Accordingly, the network being envisioned here should be established with the following concepts in mind:

- Establish a network of national climate observatories in India to continuously measure all essential parameters needed for climate impact assessment, using well-calibrated and well-maintained instruments following internationally accepted scientific protocols. A network of automated sensors needs to be established by installing/deploying new platforms and upgrading the existing ones in India and the Indian Ocean to measure the physical, biogeochemical and air-sea exchange of CO_2. Observatories in the network should give at least a 2 degree x 2 degree latitude-longitude box spatial resolution over the mainland (which would call for about 60 observatories), besides a few on the islands adjoining India (Lakshadweep and Andaman Nicobar islands) and a few on the high-altitude Himalayas. Some of the observatories in the network will be the research testbeds for specific purposes such as monsoon clouds, thunderstorms, land surface processes, glacier dynamics and hydrological budgets.

- The data from the network would serve as ground truth for validating satellite retrieval algorithms. They could be assimilated with the satellite data, leading to more spatially homogeneous and contiguous data at much higher resolution. This network includes a specialised facility for developing and calibrating hyperfine spectral resolution and polarised measurements using satellites. The development work needs to be carried out with academia and industry participation.

  A selected number of observatories (say 10 to 15) of this network would serve as '***Supersites***', where all climate-sensitive parameters would be extensively measured. These supersites would represent the distinct climatic conditions and geographical sub-regions of India and represent the climate reference stations for the South Asian region.
- Following the international protocol, a dedicated calibration facility for all climate-sensitive parameters observed from the network will be established in India with industrial participation.
- A network of GHG observatories needs to be established for measuring and validating the GHGs (TCCON-type of network) over selected sites in India, representing different ecosystems. This would provide an opportunity for Indian industries/incubation centres to develop sensors/instruments and communication equipment.
- There is groundwater depletion and recharge in different pockets due to the increasing water demand. The management solutions like river interlinkage and an increase in the number of wetlands need to be observed, monitored, and modelled to arrive at future scenarios in India. Major field campaigns in the Northern India Indo-Gangetic Plains and Gujarat supported by *in situ* measurements with indigenously developed sensors need to be closely coordinated.
- In cryospheric studies, the database must be continuously updated, advanced AWS must be installed in the High Mountain Himalayan Region and indigenous techniques must be developed to measure the thickness of glaciers regularly.
- Data on GHG emissions (such as methane) from our wetlands and estuaries are not adequate for understanding and quantifying them. Thus, long-term measurements and baseline studies of the estuarine and wetland systems are necessary to understand and quantify the climate-change-induced processes.

5.1.1. A Prioritized Action Plan for Observational networks

As mentioned above, the major goal of the climate-quality observation network is to create a decades-long time series of essential climate variables (including those of climate-forcing constituents, which are not amenable to satellite-based measurements to the required accuracies) of the atmosphere, land, ocean and cryosphere through in situ measurements covering all diverse geographical terrains of India, Islands, Indian Ocean and the mountain glaciers. Such observations are essential for creating uniform baseline data required for assessing climate impacts, policy planning and execution; by way of inputs to numerical models and their calibration, validation of satellite-sensed data, calibration of algorithms, etc.

As explained above, four types of observatories would be required as part of the planned observational networks. All sensors/instruments used in this network will be standardised, calibrated against the golden standard prescribed by international agencies like WMO, IOC, etc. and monitored and serviced periodically to ensure that no deterioration in data quality or instrument artefacts occurs.

(i) Climate forcing perturbations due to aerosols, in general, and Black Carbon, the strongest and shortest-lived species of composite aerosol system in particular, remain one of the most uncertain elements of all climate models across the globe. With no satellite capabilities still available for accurate measurements of these species, ground-based networks are the only way out. This network should comprise state-of-the-art instruments to continuously measure (i) aerosol columnar spectral optical depths from visible through near IR; (ii) near-surface mass concentrations of composite aerosols (total and Particulate Matter 2.5); (iii) mass concentrations of Black Carbon and Organic Carbon from fossil (petroleum products) fuel combustion and biomass (wood, stubble, litter, dung cakes etc) burning, (iv) aerosol single scattering albedo (v) aerosol size distribution and (v) precipitable water vapour in the atmosphere. Such a network could be established (as detailed above) as a major ground-based facility, the AWS being one of its constituents. At present there are a couple of networks existing, being run by different departments following different protocols. The feasibility of bringing some of these under mega science programme could also be considered. Nevertheless, there would be a need for about 70 to 75 observatories spread across the mainland, including sub and trans-Himalayan regions and islands. These data are also important in assessing the impact on glaciers and the water cycle. The cost would be approximately ₹ 150 crores for 75 stations, including data archival at station level and transmission to a central location. Such a network would be highly valuable, especially in the context of claims indicating that Black Carbon is second only to CO_2 in global warming.

(ii) Automated Weather Stations (AWS) to consistently and constantly observe atmospheric parameters like temperature, humidity, pressure, wind, incoming and outgoing radiation, and greenhouse gases (CO_2 and CH_4). About 75 such stations (60 in the mainland and 15 in the Islands), covering all types of diverse terrains of mainland India and the Islands, to make observations representative of a minimum of 200 km x 200 km area are to be installed, monitored and maintained. The installations are planned in a phased manner as indicated in Table 5.1.1. Out of these 75, a minimum of 10 observatories will act as testbeds for research on one or more extreme atmospheric phenomena like lightning and thunder, heat/cold waves, cyclones, droughts, floods, etc. Additional sensors and instruments, if required, will be added to the 10 observatories earmarked as testbeds to ensure that all aspects of relevant climate phenomena are covered.

(iii) The Survey of India has recently established a dense network of GNSS receivers (>1000) across the country for geodetic applications. Augmentation of these stations with AWS allows us to estimate Integrated Water Vapour (IWV), a crucial parameter for the prediction of extreme events, precisely.

(iv) Radiosonde atmospheric profiling stations to measure the lower and middle atmosphere daily and cover all essential climatic variables are to be deployed co-located with at least 30 AWS stations (a minimum of one in every 400 km x 400 km area) covering diverse terrains and meteorological zones of the Indian mainland and Islands. Each radiosonde will carry standardised, calibrated sensors for temperature, humidity, pressure, wind, ozone, etc.

(v) Greenhouse gas emission observatories in all major cities, major wetlands, agricultural fields, and industrial clusters will be required. About 40 of them well spread over the length and breadth of the country to observe the emissions from different types of sources, and co-located with aerosols, AWS and Radiosonde observatories for providing complementary data, should be established in Phase I.

(vi) Ocean observatories will be of two types— (i) carrying sensors for met-ocean parameters onboard fixed platforms like moored buoys and (ii) moving automated platforms like Argo profiling floats and sea gliders carrying sensors for temperature, salinity and oxygen. Ten moored buoy platforms, 50 profiling floats and 10 gliders will need to be deployed around India to obtain a long-term series of ocean parameters. Twenty of the 50 profiling floats, all gliders and five moored buoys will also need to be equipped with additional sensors for CO_2, chlorophyll and pH in Phase I.

(vii) In order to improve upon glacier observations, 20 automated Advanced AWS and devices for measuring the thickness of glaciers continuously over long periods will need to be established till 2035. They will have to be well-spread along the Himalayas, covering major glaciers and geo-climatic areas.

Table 5.1.1: Observational Networks: A 3-Phase Plan

S. No.	**Type of Observatory**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Automated Weather Stations (AWSs)	30	2.10	30	2.10	15	1.05	75	5.25
2.	Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories	30	5.00	25	5.00	20	5.00	75	15.00
3.	Radiosonde Ascent Facility	15	12.00	10	8.00	5	4.00	30	24.00
4.	GHG Emission Observatories	20	16.00	10	8.00	10	8.00	40	32.00
5.	Moored Met-Ocean Data Buoys	5	15.00	3	9.00	2	6.00	10	30.00
6.	Ocean Gliders	5	20.00	3	12.00	2	8.00	10	40.00

7.	Argo Floats	20	6.80	20	6.80	10	3.40	50	17.00
8.	Glacier Observatories	10	15.00	5	7.50	5	7.50	20	30.00

Note: As per the goals of the MSV-2035 Exercise, the Climate Research community of the country has put forward in this document a plan for Mega Science Projects/activities for the 2020-35 period. A tentative 3-Phase Budget (each Phase lasting for 5 years) was also worked out, which has been presented in Table 5.1.1 above, and also in Tables 5.2.1, 5.3.1, 5.4.1, 5.5.1, 5.6.1, 5.7.1 and 5.8.1 below. However, considering the time taken in preparing this first-ever Mega Science Vision Report on Climate Research, the time duration of the three phases and the phase-wise distribution of various items may change. The total projected requirements will, however, remain as proposed in these Tables.

5.2. Indigenous development of sensors and instruments

Traditionally, the concerned groups developed the required instruments for scientific research in India based on physical principles and the problem to be investigated. This trend led to new instruments being developed and used, giving the much-needed insight into the quality of data collected and the uncertainties and errors involved. Unfortunately, for various reasons, such instruments did not cross the boundaries of the laboratories where they were developed and reach the industries for mass production. In addition, due to the generous funding by various agencies, the pressure on scientists to deliver quick results and the easy availability of foreign ‘plug and play’ type instruments with built-in first level of data processing and computer interface, the trend shifted to the procurement and use of such instruments. Often, instruments are used without knowing the principle of operation, the built-in assumptions, the data deduction processes and their limitations and applicability in specific problems. Consequently, such instruments were not calibrated for years, leading to incorrect data being reported in national and international journals, often leading to questions on the credibility of Indian science. Unfortunately, this has also resulted in the loss of practice of developing scientific instruments in India.

Today, virtually no company in India manufactures quality scientific instruments for climate research due to the lack of collaboration between scientists and industries. Despite the considerable manpower engaged in climate research, the scientific outputs and the total funding over the past couple of decades, instrument development has been (conveniently) neglected. Thus, billions of rupees have been spent and continue to be spent on procuring instruments manufactured elsewhere. A significant portion of this amount could have been spent on developing instruments within the country, resulting in industrial and economic development. Once the scientific potential of indigenous instruments is established internationally through peer-reviewed publications and inter-comparison experiments, markets for these instruments outside the country could also be explored. This calls for a conscious policy decision for other reasons as well. Since most of the (if not entire) research is state-funded, a policy encouraging or incentivising collaborations between researchers and industry is necessary to reduce the dependence on other nations for the instruments needed for research and to promote innovations in the design and manufacturing of novel instruments that can increase the accuracy of measurements quickly.

Accordingly, it is proposed that India develop a significant portion, if not all, of the scientific instruments needed for the national climate observatories mentioned above. The following outlines a conceptual approach to this.

- As a policy, it should be mandated that most of the instruments for measuring parameters relevant to climate forcing and impact assessments should be made in India. This mandate can be achieved through joint efforts of (a) national institutions and academia responsible for selecting the type of instruments, their specifications, accuracy, and mode of operation for stand-alone field use as well as analysis protocols, and (b) industry to manufacture the instruments with features competing with those available elsewhere. The policy should also specify the rationale and procedure for guaranteed purchase and guaranteed pricing of India-made instruments for a minimum period.
- Students should be encouraged to get involved in each stage of instrument development to enable them to obtain hands-on training through industrial internships, which could form part of the curriculum. A ‘design and development concept proving model’ should be made part of the curriculum for Master's students. Institutes should be encouraged to tie up with industries to provide students with hands-on experience in fabrication and testing. This would inculcate innovative thinking in the young minds and a culture of developing instruments rather than choosing ready-made instruments.

5.2.1 A prioritised action plan for Indigenous development of sensors and instruments

- The major goal of indigenous development of sensors and instruments is to inculcate the culture of making the necessary instruments for observing climate variables, aerosols, greenhouse gas emissions, etc., in India. Though Indian engineers and technologists have the capability for conceptualising design and making prototypes of instruments (some of which have already been demonstrated successfully), they are not often translated into final industrial products, leading to mass production. However, a few exceptions involving the transfer of technology from labs to industry in the country are encouraging. For example, the technologies developed at NIOT (automatic profiling floats for ocean observations), IMD/ISRO (AWS), etc., have been transferred to the industry, but most of them have not reached the market yet. The sensor/instrument development plan is being proposed here in a phased manner as indicated in Table 5.2.1.
- In Phase I, all technologies transferred to the industry will be identified and analysed to understand why those technologies/products are still not in the market. A report will be prepared based on the analysis, suggesting ways and methods for facilitating their manufacturing by the Indian industry. A series of training programmes for young engineers/ researchers/scientists will be organised so that adequate human resources will be ready by Phase II. The outcome of this phase would be a comprehensive report based on the list of technologies already transferred to the industry and what needs to be done to facilitate their manufacturing by the industry in alignment with adequate human resources.
- During Phase II, the research and observational groups will identify the requirements of type and quantity of instruments and sensors required for the use of Mega Science projects and provide the specifications, expected accuracies and expected longevities of autonomous instruments. Proposals to develop such instruments and sensors will be called

from the research and academic institutions and the R&D wings of the industry. The proposals will be evaluated, and projects will be awarded based on competency and workability. A series of new R&D projects focusing on developing the sensors and instruments necessary for the use of observation and analytical laboratory components of Mega Science projects would be the result of this. Prototypes of various sensors/instruments will be developed. The development of sensors and instruments will be targeted in this Phase based on the feasibility and the expected quantum required for climate observations. Field testing, inter-calibration exercise, etc., will be carried out. Their quality, sturdiness and durability will be further tested and certified to be ready for industrial manufacturing. The outcome of Phase II would be a set of newly developed research-quality sensors and instruments ready for deployment.

- During Phase III, the newly developed sensors and instruments will be deployed using Mega Science projects. The outcome of Phase III would be a document containing the list of tested, certified research-quality sensors and instruments developed as part of the Mega Science Vision Exercise by different research, academic and industry groups.

Table 5.2.1: Indigenous Development of Sensors and Instruments: A 3-Phase Plan

S. No.	**Type of Sensor/Instrument**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Automated Weather Stations (AWSs)	12	4.20	30	1.50	60	3.00	102	8.60
2.	Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments	10	6.00	25	15.00	50	30.00	85	51.00
3.	Radiosondes	15	15.00	25	6.00	50	8.00	90	29.00
4.	Profiling Floats with T, S and Chlorophyll sensors	10	7.50	30	8.00	60	10.00	100	25.50
5.	Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity	5	1.75	15	5.25	25	8.75	45	15.75
6.	Radiation Sensors (SW & LW, Incoming and Outgoing)	20	1.00	50	2.50	50	2.50	120	6.00
7.	Micro Pulse LIDAR with Dual Polarisation Capability	5	7.50	5	7.50	10	15.00	20	30.00
8.	All Sky Imagers for Cloud Fraction	20	1.00	50	2.50	50	2.50	120	6.00

9.	Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor)	5	2.00	10	4.00	15	6.00	30	12.00
10.	Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator	10	3.50	20	7.00	20	7.00	50	17.50
11.	Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations	5	5.00	10	10.00	10	10.00	25	25.00
12.	Lower Atmospheric Wind Profilers	5	15.00	10	30.00	15	45.00	30	90.00

5.3. Remote sensing and satellite-based monitoring

India has diverse geographical and environmental features, as well as vast terrains that are difficult to access. In such a case, other solutions are available than operating sophisticated observatories or maintaining a network of observatories. Although such observatories provide accurate data on most parameters with extensive temporal resolution and coverage, the spatial coverage remains to be improved and is slightly better than point observations. However, sub-regional/regional/global climate impact assessments call for contiguous data in the spatial domain. This can be realised through dedicated satellite-based measurements and continuous data validation from ground networks.

- Space technologies for Earth observation provide essential inputs to address various aspects of climate research. Several sophisticated satellite sensors (both Indian and international) have been dedicated to atmospheric studies in the last decade. The Indian satellite systems are currently generating a few Essential Climate Variables (ECVs), but not all of them are required from the ocean, atmosphere, land and biosphere. The challenges in space observations include designing and placing adequate and accurate multiplatform observational systems and developing retrieval techniques for Analysis Ready Data (ARD) Products of ecvs with precise calibration and validation. Efforts are also to be made to take advantage of the missions planned by other agencies like NASA, JAXA, ESA, etc., through cooperation or collaboration.
- Continuity in the missions to ensure long-term measurements is another crucial aspect of generating quality data for climate research. Currently, the research requirements are met by using parameters from wide-ranging sensors with conflicting accuracies, spatial and temporal resolutions and durations. That leads to widely different and sometimes contradictory inferences. Several atmospheric parameters must be measured simultaneously using an intelligently designed satellite platform to cover several climate science questions. For example, estimating radiative fluxes at the Earth's surface from satellite measurements requires trade-offs between the utilisation of multi-spectral observations and atmospheric measurements that are more difficult to implement at large scales if we have co-located data from the same satellite.

- In addition, the auxiliary data needed by the models, such as aerosols and spectral surface albedo, water vapour and ozone profiles, and cloud properties, are taken from other sources and can add to the complexity of uncertainties. Solar radiation reaching the Earth's surface is the primary energy source for the land surface and water cycle. Solar radiation incident at the Earth's surface determines the surface temperature and sensible and latent heat fluxes that govern most dynamic and hydrologic processes. Hence, multi-sensor retrievals became increasingly relevant and are being widely used. However, differences in pixel size, time of measurements, angle and time of observations are some challenges the climate science community often faces while using multi-satellite data. Another example is the requirement to measure sea surface temperature, sea surface salinity, chlorophyll concentration in the water, pCO_2 content of the seawater, sea level and surface wind vectors from a single satellite to avoid such issues.
- Although an exhaustive list of observations is required to meet the requirements of climate research, a few high priority future sensors necessary for climate studies are being highlighted here.
    - (a) An indigenous space-based GHGs and Aerosols Monitoring **"E*nviroSat mission*''** with a constellation of satellites, comprising very high spectral resolution sensors, multi-angle/multi-polarisation sensors and spaceborne Lidar, which can provide frequent coverage over India through polar/low-earth inclined orbits is proposed.
    - (b) "***Hydrology-Train or H-Train***" in constellation mode is needed to assess various dimensions of water manifestation in ecosystems with several satellites/sensors listed below:
        - (i) A 'Rain Radar' (13.6 GHz Ku bands at a spatial resolution of 5 km and a swath 300 km) to estimate the rain in three dimensions and help measure rain rate with greater sensitivity.
        - (ii) Large-scale assessment of surface soil moisture using an 'Active Passive Microwave system' (Radar and Radiometer combination) with real aperture Radar in the L band at a spatial resolution of 1 km and a Passive microwave radiometer (1.4 GHz) with spatial resolution ranging from 5 to 10 km and swath more than 1000 km. This instrument provides information on the surface soil moisture and land surface temperature.
        - (iii) A 'Wide Field SAR' at 25 m resolution and >500 km swath to assess the water spread in rivers and reservoirs to assess water storage and river flow.
        - (iv) A Ka band altimeter like SARAL Altika for accurate measurements of river discharge. Simultaneous measurement from Altimeter and SAR in constellation would improve river flow modelling.
        - (v) A dedicated '***Cloud and precipitation mission***' with frequent overpasses over the tropics.
    - (c) An Indian '***HimMission***', a constellation of multi-frequency SAR satellites, radar imaging altimeters and high-resolution scatterometers to get the best estimates of daily discharge from velocity, calving and margin changes in the Indian Himalayan region.
    - (d) In addition, a '*Continuity mission*' of space-based scatterometers (SCATSAT follow-on) is necessary as Ocean Surface Wind is an important ECV. The science arising from this mission has been beneficial to the global scientific community

under the Committee on Earth Observation Satellites (CEOS), a coordinated effort by various space agencies. Also, the INSAT series of satellites (4th generation) needs to be taken up as a '*Continuity mission'* with enhanced imaging capability for atmospheric research over the Indian region.

- The utilisation of polarisation in sensors can significantly enhance the accuracy of retrievals. For example, the properties of aerosols, clouds, radiation budget, surface properties, altitude trace gas concentration and so on, especially over the heterogeneous landmass, vary with season. Retrieval of variables over vast continents remains a challenge due to complicated and irregular terrain characteristics and high and heterogeneous surface reflection compared to atmospheric back-scattering. The retrieval algorithms used in conventional satellite sensors for continental regions are not free from the high reflectance effect. Hence, these algorithms lead to significant uncertainties in the retrieved parameters and have limitations in their global applicability. A sensor that can measure polarised components of reflected radiation from the Earth at different angles will be a significant step forward.
- Large viewing angles (thereby looking through a larger amount of atmosphere) enhance sensitivity to atmospheric scattering effects. The intensity of the polarised light reflected by a land surface is relatively low and comparable to or lower than that reflected by aerosols and clouds. This enables the retrieval of several climate-relevant parameters over land, including the deserts.
- Scientists with adequate expertise in the above subject (from national institutions and academia) could be grouped to conceptually design such satellite sensors in a joint effort between industries and space agencies. In the meantime, the scientists should work on and finalise the retrieval algorithms with desired accuracies and operational conveniences to the international community's acceptance (in the form of peer-reviewed publications of the techniques). The data from the national network described above can validate retrieved data products.

5.3.1. A prioritised action plan for Remote sensing and satellite-based monitoring

Space-based sensors at multiplatform observing systems are needed to generate data on ECVs over the Indian region.

During Phase I, detailed sensor system studies would be required to be initiated for the design of required sensors/instruments, including satellite constellations over the Indian region. This may call for brainstorming with sensor designers and domain experts to firm up the technical specifications vis-à-vis global availability of space-based monitoring sensors, including airborne and satellite-based sensors. The Department of Space/ISRO can take up the satellite mission/s based on the detailed report generated as a Mega Science project.

During Phase II, the actual fabrication, development and launch of identified sensors need to be executed through Indian industry and start-ups in collaboration with ISRO. The ground stations for data reception and data dissemination will be taken up under the mandate of the Department of Space. In parallel, the Indian scientific community will work on algorithm development for the retrieval of geophysical and biophysical parameters using state-of-the-art techniques like AI/ML/Deep Learning, etc.

During Phase III, the newly available sensors and instruments data will be made available to the researcher community in the form of analysis-ready data products. The new data will provide continuity to long-term climate-qualified datasets over the Indian region. The data will be made available to the academic and researcher community through a country-level centralised data centre.

While implementing the action plan, by the end of Phase-III, relevant experts will produce and review a detailed document with improved scientific findings and understanding of climate research. In addition, a policy framework and implementation plans will be worked out based on the improved scientific understanding of climate over the Indian region.

Table 5.3.1: Remote Sensing and Satellite-based Monitoring: A 3-Phase Plan

S. No.	**Algorithm development activities**	**Phase-I**		**Phase-II**		**Phase-III**		**Total Cost**
		Activities	Cost	Activities	Cost	Activities	Cost	
1.	GHG and Aerosols Monitoring Mission	Detailed Sensor System Studies and Instrument Design	5.00	Fabrication, Development, Launch-related Infrastructure	20.00	Analysis-ready Data Products, Dissemination, Climate Research Studies/ Projects undertaken by academia and researchers comm-unity/ Policy Frame-Work and Implementation Plans	10.00	35.00
2.	Hydrology Constellation		5.00		30.00		10.00	45.00
3.	Cloud and Precipitation Mission		5.00		20.00		10.00	35.00
4.	Himalayan Climate Mission		5.00		25.00		10.00	40.00
5.	Space-based Scatterometer Indian Mission		5.00		20.00		10.00	35.00
6.	Continuity Missions from Geostationary Platform	Improved Sensor Resolutions	5.00		25.00		10.00	40.00

5.4. Development of indigenous India-specific climate models

India urgently needs region-specific climate and impact models, which should be distinct from the existing models in India (mainly adapted from the USA or Europe, with limited scope for customisation for regional purposes or providing different types of inputs than those envisaged by their original developers). These models need to be used for specific applications like monsoon prediction or ocean dynamics.

The idea of developing a climate research model from first principles is not to rewrite the code of an existing model. Here, scientists need to provide their scientific expertise to the IT industry to develop the code. At the outset, developing climate research models from first principles might look like a ‘reinvention of the wheel’ because several models are already available to serve the purpose. But to inculcate the capacity in the younger generation to think from the first principles, to conceptualise and implement those ideas in practice, and to encourage them to dive down to the deeper depths of model development, numerics and code building, such an approach is essential. Of course, such attempts may not pay immediate returns but will pave the way for inculcating original thinking and innovation. Hence, this project should not only be looked at from the point of immediate usability of the model for climate research but also from the angle of capacity development. This will bring plenty of scope for capacity building/HR development by involving students at every stage of model development.

Numerical models that predict/project the future climate globally or regionally are developed to predict the atmosphere, ocean, and land processes. These are widely known as Earth System Models. They account for most physical, chemical and biological changes occurring in the atmosphere, land and ocean due to the projected/perceived increase in anthropogenic CO_2 and other greenhouse gases. Several expert groups, mainly from the western hemisphere, have developed numerical models to predict the components of future climate, like temperature, weather events, precipitation, droughts, food production, etc. It is estimated that more than two dozen major models are used to simulate the components of future climate in the scenarios of different rcps suggested by the United Nations (UN) Panel on Climate Change. Though several improvements have been constantly incorporated into these models, they have yet to succeed in simulating the present climate in all aspects, especially at regional levels. All types of models (radiative transfer models, dispersion models, transport models, weather prediction models, climate models and so on) are proposed to be developed indigenously. The Artificial Intelligence / Machine Learning approaches can be intelligently used in this effort. There is a strong need to build the capacity to develop both global/regional climate models and sectoral impact models.

Selecting the correct input through the experience gained from the vast datasets offers a wide opportunity to use AI/ML in numerical weather prediction (NWP). AI/ML could be the most useful tool to identify the unresolved scale errors in weather models that fail to recreate the physical phenomena fully. The need for better parameterisations of physical processes, especially cloud systems and air-sea exchanges, introduces climate model simulation uncertainties. The advent of high-performance supercomputers, high-resolution Earth System Models (ESMs), and big data analytics offer a promising future for ML and AI applications in climate research.

The expected improvements in the indigenous model are:

(i) A telescopic model that allows seamless lower temporal and spatial resolution at a global scale and higher resolution at a regional scale. Such an approach will be able to simulate local characteristics such as the climate in a city, in a mountainous region and along the coast.

(ii) Better numerical schemes to solve the equations.

(iii) Improved computer code to take advantage of the improvements in computer technologies, for example, the GPU-based code.

(iv) Better parameterisation of the processes based on the observations and data from the Indian region. The current models depend on the parameterisations created based on the observations and data from mid and high latitudes.

(v) Reducing or eliminating the approximation of physical processes which is important for the accurate simulation of past/future climate.

(vi) Reduced uncertainties in climate sensitivity and reducing uncertainties in radiative forcing, particularly that associated with aerosols.

(vii) The most significant uncertainty in the existing climate models is their inability to simulate clouds correctly, especially the physics behind the clouds and how they interact with the aerosols. The uncertainty is more severe in tropical regions and can be minimised/resolved by utilising the data from recent observations in India.

(viii) More realistic representation of vegetation processes and soil moisture.

(ix) Improved ocean simulations, particularly in the Southern Ocean and the mixed layer dynamics. This is important for the uptake of heat and carbon from human activities and for the simulation of correct sea surface temperatures, which are crucial for determining the energy transfer across the ocean-atmosphere interface.

(x) Use of artificial intelligence to minimise the empirical formulations of the processes accounted in the model.

Considering the complexities in developing a model from first principles, it will take at least ten years to test and fine-tune it. More people with expertise in land-ocean-atmosphere dynamics, applied mathematics, statistics, and, more importantly, computer coding need to be involved in the model development process to generate and implement new ideas.

5.4.1. A prioritised action plan for the Development of indigenous India-specific climate models

The main objective of developing indigenous India-specific climate models is to inculcate the culture of model-building in the country by utilising sound knowledge in physics, mathematics, ecology, chemistry, computer science and computer programming in the country. It is akin to what has been done by the research and university consortia in the USA, UK, France, Japan, China, etc. Over decades in the past to build and improve the numerical models used for climate research at present. At the outset, this will sound like ‘re-inventing the wheel’, but it will aid in developing multiple capabilities to deliver a unique model tailormade to handle the climatic conditions specific to India and her surroundings. For example, monsoons are the major seasonal phenomena in the region that are not well reproduced by the existing climate models despite their adoption to predict the monsoons. The shortcomings may be because of their limitations in incorporating local physics and dynamics specific to the region to the required extent. In addition, new approaches such as AI/ML will also be explored.

To achieve these targets, during Phase I, a consortium of Indian research institutions and academic institutions will be formed through brainstorming workshops to identify the basic components of the indigenous climate model. Phase I will conclude by creating a clear flow diagram of the Indian climate model and addressing calls for expression of interest in developing specific components of the indigenous model.

During Phase II, the interested groups will be asked to submit detailed proposals detailing the physics, dynamics and parameterisation of the variables about the component of interest. There will not be any restriction on selecting more than one institution or group to develop the same component. Phase II will end with evaluating specific components developed by each group and selecting the best physics, numerical technique/s, parameterisations, etc. for each of the components of the indigenous model. The institutions and industries with expertise in computer coding and integrating various components developed during the previous phase will be asked to build the indigenous India-specific climate model using modern computing techniques like GPU computing, quantum computing, etc. Phase II will conclude by rolling out the indigenous model for the use of the research community after several test runs and error estimates.

During Phase III, the new model will be available to the community.

Table 5.4.1: Development of Indigenous India-specific Climate Models: A 3-Phase Plan

S. No.	**Type of Activities leading to the development of the Indigenous India-specific Model**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Workshops and Brainstorming Meetings for preparation of the Flow Diagram	10	5.00	-	-	-	-	10	5.00
2.	Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed	-	-	50	30.00	-	-	50	30.00
3.	Proposals for development of codes for individual components, testing and integration, and implementation of the Model	-	-	-	-	24	30.00	24	30.00

5.5. Improving the existing models

Substantial progress has been made in improving the existing models during the past decade. For example, the development of a climate model by transforming the seasonal climate forecast model (CFS) of NOAA, USA coupled with an ocean circulation model (Modular Ocean Model) developed at Princeton University, USA and refining with the incorporation of ocean biogeochemistry. The model is named "The Earth System Model (ESM) of the Ministry of Earth Sciences (MoES)”. The radiatively balanced ESM version 2 (ESMv2) provides the modelling framework to address critical scientific questions related to long-term climate change. It allows us to test hypotheses and draw conclusions on past and future climate systems. Also, it is useful to determine whether abnormal weather events (floods/droughts) or storms result from climate change or are just part of the routine climate variation.

Though ESMv2 fine-tuned the simulation of the South Asian Monsoon, global radiative balance, marine biogeochemistry, polar sea-ice distribution, Atlantic Meridional Overturning Circulation, aerosol forcing, land use and land cover changes and succeeded in reducing the cold bias in sea surface temperatures, a common problem observed by all the major models participating in CMIP, it still requires further improvements in the role of land use, pollution and nutrients. Addressing such issues could easily hit a plateau due to the limited flexibility of the already developed model, with its specific gridding philosophy, specific numerical technique(s) to solve the equations, computer code, etc. Therefore, improved models that emphasize the model physics that best responds to the regional phenomena and enhance the flexibility in gridding, numerical techniques, and computational efficiency are proposed. The enhanced model should also strive to represent the other aspects of the climate system, like the tipping points and nonlinearities not always captured in the existing climate models.

The availability of super-computing facilities is vital for the development of indigenous India-specific climate models as well as for improving the existing models. The present capabilities of petaflop scale computing power need to be upgraded in a graded manner to exascale computing in the next 10-15 years. The present capabilities of climate services, and the first projections of future climate change by an Indian climate model, could be achieved only because of the availability of high-end computers. Considering the fast-evolving super-computing technology, USA has installed the first exascale computer at Oak Ridge National Lab. The higher computing power of hundreds of petaflops to exa-scale computing will significantly aid in applications in weather and climate domains as their predictions and projections demand multiple ensembles at finer spatial and temporal resolutions.

5.5.1. A prioritised action plan for Improving the existing models

Existing Earth System Models are being used in India. For example, the ESMv2 is a radiatively balanced atmosphere-ocean-land-sea-ice coupled model with ocean biogeochemistry. The basic model was adopted from NOAA, USA's CFS model. However, further improvements are needed to accurately account for and simulate the interactive effects of land use, vegetation, aerosols, oceanic nutrients and plankton, air pollution, and their transport in modifying the climate over the Indian region. On top of it, a relatively coarser resolution of the global coupled model cannot resolve complex topography features like Western Ghats, and Himalayan orography, which are crucial for a realistic representation of the Indian monsoon. A higher resolution model is also necessary to get the extreme weather and climate events right under changing climate. In summary, the present version lacks interactive carbon cycle which is essential to simulate changes and biospheric feedbacks associated with terrestrial ecology, atmospheric greenhouse gas, and ocean biogeochemistry responses to fossil fuel emissions and land use change. Eventually, such models should be able to interact with the measured data dynamically.

During Phase I, brainstorming meetings will be conducted involving various research institutions and academia to further develop ESMv2 by incorporating new Earth system components and develop a community ESM. The community ESM will include interactive carbon cycle, aerosols, land-ice components including Himalayan cryosphere and hydrology.

During Phase II, proposals will be invited from interested groups to develop community ESM. In addition, proposals will be invited to develop tools for utilising climate model outputs for various sectorial applications and climate impact assessment.

During Phase III, a hybrid (Physics+ML based) ESM will be developed. GPU-based computing will be implemented to excel in performance and achieve higher resolution to provide climate information at regional and local scales. During this phase, upgrading the existing petaflop-scale computing to an exa-scale computing facility is also proposed. Customisation of climate model outputs will be carried out for various sectoral applications. The outcome of Phase-III would be a very high-resolution, hybrid (physics + ML) Earth system model that can generate climate projections at regional and local scales over the 21st century and beyond for robust climate risk assessments and various sectoral applications.

Table 5.5.1: Improving the Existing Models: A 3-Phase Plan

S. No.	**Type of Activities for Improving Existing Models**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Workshops and Brainstorming Meetings for incorporation of new Earth System components	10	5.00	-	-	-	-	10	5.00
2.	Proposals for the incorporation of new Earth System Components, and Community Model Development	-	-	50	30.00	-	-	50	30.00
3.	Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based)	-	-	-	-	10	30.00	10	30.00
4.	Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale	-	-	-	-	10	10.00	10	10.00

5.6. Thematic mega-campaigns/experiments

Field experiments are an essential component of any evolving research programme. The ideas and hypotheses emerging from the research and model simulations are tested, and the outcome is then fed back to the system to improve the observations and modelling to address the knowledge gaps. Several national and international field campaigns/experiments have been conducted to study the climate. The Monsoon Trough Boundary Layer Experiment (MONTBLEX) was a multi-institutional, all-India coordinated programme conducted during 1989 to study the atmospheric boundary-layer processes in the monsoon trough (MT) area of northern India. The Bay of Bengal Monsoon Experiment (BOBMEX) and Arabian Sea Monsoon Experiment (ARMEX) under the Indian Climate Research Programme (ICRP) were carried out from 1999 to 2005. The observational component of the Indian Ocean Experiment (INDOEX) on land, sea and air were designed to assess the chemical, physical, and optical properties of aerosols over the Indian Ocean.

The Integrated Campaign for Aerosols, Gases and Radiation Budget (ICARB) was one of the largest multi-institutional, multiplatform field experiments carried out during 2006, under the ISRO's Geosphere-Biosphere Programme. The Continental Tropical Convergence Zone (CTCZ) programme was a national field campaign under ICRP that was carried out from 2007 to 2008. Cloud-Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), a national experiment, was carried out in three phases from 2009 to 2011. RAWEX–GVAX (Regional Aerosol Warming Experiment–Ganges Valley Aerosol Experiment) was jointly conducted during 2011–12 by the US Department of Energy, the Indian Space Research Organization and the Department of Science and Technology. More recently, an Indo-UK collaborative campaign, South-West Asian Aerosols Monsoon Interaction (SWAAMI), has been conducted to explore the aerosol-cloud interaction processes over the South Asian region during the transition phase of the Indian summer monsoon and to explore its implications for the monsoon and the hydrological cycle. Under the same collaboration, another project named the Bay of Bengal Boundary Layer Experiment (BOBBLE) was conducted to examine the impact of ocean processes in the Bay of Bengal (BOB) on the monsoon system. Similarly, Ocean Mixing and Monsoon (OMM) and Air-Sea Interactions Regional Initiative (ASRI) were conducted by India and the USA simultaneously by deploying research ships to understand the interactions between the upper ocean and the atmosphere in the Bay of Bengal from 2013 to 2015.

Considering the experience gained from the previous field experiments, the Mega Science field campaigns being proposed here are based on the following concepts:

- The Mega Science field campaigns should have the participation of several institutions across the globe. Field experiments should cover continental, marine and remote environments. Various platforms such as research ships and aircrafts, besides a network of ground-based observatories, should be considered. Investigations should involve meticulous planning regarding execution, intuitive data analysis and interpretation. Each experiment is expected to provide a new direction to research, and the outcome should aim for discoveries with significant implications.
- Each campaign should have a distinct objective and aim to address an unprecedented grand challenge. Some of the unique issues that can be addressed are the impact of radiatively active atmospheric constituents on climate and air quality, the interaction of radiatively active atmospheric constituents with precipitation, moist convection and atmospheric chemical processes, the interaction between ecosystem processes and changes in the climate system, interaction between changing climate, hydrological systems and their management, implications of climate change for energy systems, strategies for mitigation and adaptation, melting ice and global consequences, clouds, circulation and climate sensitivity, carbon feedbacks in the climate system, weather and climate extremes, regional sea-level change and coastal impacts, and warming of oceans, deoxygenation, acidification and their effects on life underwater.
- Each campaign should select relevant processes from the above list, as justified by the outcome of the research. The campaigns should be planned and supported with a peer-reviewed science plan and implementation plan prepared in advance, at least a couple of years before their proposed execution.
- A national institute should set up a data centre to aggregate and archive the data from the field campaigns and also from past field campaigns and observation systems. This will

ensure data availability for climate-related research and for the selection of the best possible adaptive measures.

5.6.1. A prioritised action plan for Thematic mega-campaigns/experiments

The major goal of thematic mega-campaigns/experiments is to understand the physical and chemical processes and their dynamics in shaping the weather and climate in the region and translate those into mathematical equations in the model to reproduce the observations. Since the climate is influenced and controlled by land, atmosphere, ocean and glaciers, such thematic mega-campaigns will be conducted over all of them in a combined fashion or individually.

During Phase I, it is proposed to undertake a mega-campaign involving research and academic institutions to understand the process involved with the aerosols and pollutants in controlling the radiative components, formation of clouds and precipitation. Ground and upper air observations of aerosol and pollutants as well as all weather and climate parameters will be made at 8-10 suitable locations well spread over diversified geography and climatic conditions in the country. Interested collaborators from abroad will also be invited to join the mega campaign and associated research. The mega field campaign will also conduct surveys involving medical teams in the localities to understand the effects of aerosols and pollutants on human health. The campaign will continue for a minimum period of 3 years to ensure the quality and stability of data and the inferences drawn from them.

There is groundwater depletion and reduced recharge in different pockets due to the increasing water demand. Management solutions like river interlinkage and an increase in the number of wetlands need to be observed, monitored, and modelled to arrive at future scenarios for India. A major field campaign in the Northern India Indo-Gangetic Plains and Gujarat, supported by *in situ* measurements with indigenously developed sensors, will be conducted during Phase II. The campaign will be organised through a well-coordinated project involving several research and academic institutions.

Several aspects of air-sea interaction, ocean mixed-layer process, ocean acidification and its impacts on marine life, etc. need to be understood better to make projections for the future. A mega air-sea campaign involving *in situ*, satellites, aircrafts and research ships will cover India and the Indian Ocean region over 3 years during Phase III. This campaign will utilise the observing systems detailed in section 5.1 and also some other systems for making any specific observations. Collaborators from other countries will also be involved in making observations, data analysis and research.

Table 5.6.1: Thematic Mega-Campaigns/Experiments: a 3-Phase Plan

S. No.	Thematic Mega-Campaigns/Experiments	Phase-I		Phase-II		Phase-III		Total	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	For studying impact of radiatively active atmospheric constituents on climate variables and air quality (No. of campaigns/experiments)	10	10.00	15	15.00	20	20.00	45	45.00
2.	For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments)	2	5.00	3	10.00	4	15.00	9	30.00
3.	For studying warming of oceans, deoxygenation, acidification and their effects on life underwater (No. of campaigns/experiments)	10	17.00	15	25.00	20	40.00	45	82.00
4.	For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments)	5	10.00	10	20.00	10	20.00	25	50.00
5.	For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India)	-	-	10	20.00	10	20.00	20	40.00

5.7. Carbon-neutrality research

India has pledged carbon neutrality by 2070 at COP26 in Glasgow, UK. Achieving carbon neutrality is challenging for India, considering the economic growth required to support the world's largest population. From emitting more than 660 million tonnes of carbon dioxide in 2020, India has to lower the emissions to 360 million tonnes in 2030 and net zero within five decades. Unless carbon-neutrality becomes a national movement involving industry, state governments and researchers/academia, it would be difficult to achieve these targets.

- Several areas require attention, including low-carbon energy technologies, from hydrogen fuel cells to batteries; market-based mechanisms to control emissions; and modelling to help local governments and industries set realistic targets for cuts. We need to study the sections of the population most affected by the transition and help them to cope. In other words, accelerated research will be required to establish the path to a more just and inclusive transition.

- Strengthening basic research and research on cutting-edge technologies such as nuclear fusion and other nuclear energy paradigms, smart grids and new materials and formulating an action plan to ensure the achievement of carbon neutrality is an immediate necessity. Another area of focus for researchers is carbon capture and sequestration technologies which are essential for achieving the goals. Fossil fuels, including coal, oil and gas, still account for 75% of the energy consumed in India. So, a large part of carbon emission needs to be compensated by carbon capture and paired with carbon capture and sequestration or offset by new forest growth and technologies that can suck CO_2 directly out of the atmosphere. Focused research is essential in these areas as well. In addition, modelling and measurements for resource assessment of various forms of clean energy besides wind and solar need to be undertaken towards viable market models to achieve the desired carbon neutrality goals by 2070.
- Creating a vast research infrastructure to achieve the ambitious climate goals by setting up carbon-neutrality research institutes or aligning the research of existing institutions and academic centres to focus on one or more aspects of carbon-neutrality.
- It might also be required to accelerate research to enhance the efficiency of traditional coal-based technologies to reduce their emission levels.

5.7.1. A prioritised action plan for Carbon-neutrality research

India needs to achieve carbon neutrality by 2070, as pledged at COP26. Though the growth in renewable energy sources like solar, wind and nuclear has been at a faster rate in recent years in the country, it will not be possible to eliminate the emissions from fossil fuels which will continue in 2070 as well. Hence, methods like carbon sequestration by directly or indirectly capturing carbon from the atmosphere would be required to achieve the neutrality targets. It is proposed that two aspects of carbon sequestration be concentrated upon during all three phases of the mega research programme on climate. They are (i) developing technologies to directly capture the carbon from the atmosphere and bury that in the sediments over land or ocean and (ii) researching on faster-growing plants, which can absorb carbon efficiently, to facilitate quicker forestation.

Table 5.7.1: Carbon-neutrality Research: a 3-Phase Plan

S. No.	**Type of Activities**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies	8	15.00	5	20.00	10	35.00	23	70.00

5.8. Science of climate change adaptation and resilience

India is a climate change hotspot due to its proximity to the tropics, and high development deficits (e.g. low income, malnutrition, high population pressure and a large number of people engaged in climate-exposed occupations). The impacts of climate change on every sector of the economy and society are also being increasingly felt. For example, the agriculture sector is already feeling the negative effects of climate change. Some components of food systems (e.g., lower production through losses in crop yields) are already negatively affected by changes in temperature, precipitation and extreme events, whereas other components of the food systems (e.g., trade, GDP) are also projected to be impacted at higher levels of warming. These negative impacts are further exacerbated due to policies that lock farmers into sub-optimal and environmentally harmful resource-intensive practices. Further, impacts are disproportionately felt by farmers with small holdings, women farmers and people living in marginal areas.

Although state and national level adaptation plans and policies are available, which are also being implemented, there are several gaps in terms of:

1. Quantification of short-term and medium-term impacts of climate change on various key sectors (particularly climate-exposed sectors like agriculture, fishery and in climate exposed regions like coastal regions, high mountain regions, etc.), and development of suitable adaptation responses in consultation with local communities/stakeholders;
2. Suitability of adaptation action to reduce risk and develop resilience to climate hazards in the short to medium term;
3. Understanding of adaptation responses implemented by individuals, state, or non-state actors is needed to know whether they are effective in reducing the climate-related risks or they are leading to maladaptive outcomes, further reducing the resilience of communities to climate change;
4. Designing adaptation responses for the future by considering future global warming levels, and the effectiveness of various adaptations in a warmer world, including understanding the limits of adaptation.
5. Developing methodologies for measuring and quantifying the extent of loss and damage that happens when adaptation limits are reached, or when extreme events destroy lives and livelihoods of communities.
6. Advancing the climate attribution science to understand whether the extreme events had a climate change fingerprint.

A research programme on adaptation and resilience building will therefore have the following main components:

1. Measurement of the impact of current and future climate change on key sectors, regions and vulnerable people by using climate change science, particularly attribution science which enables one to quantify the extent of climate change fingerprint in an event (e.g., how a particular extreme event, e.g., a heatwave was more likely due to anthropogenic climate change); and social sciences to understand the human and societal consequences of such climate impacts;

2. Development of indicators and metrics, and frameworks and implementing them for all national/state/local level climate change adaptation programs for measuring effectiveness of adaptation in reducing climate risks and developing predictive ability to know when adaptation can become maladaptive and increase risks further;
3. Development of models and scenarios for measuring and quantifying the feasibility and effectiveness of future adaptation (at higher global warming levels) and development of predictive abilities to know when limits to adaptations are being reached because of hard physical limits (e.g., when salt water intrudes into freshwater lenses in coastal islands, or when glaciers on which communities depend for irrigation melt completely).
4. Development of methodologies for quantifying loss and damage from both slow-onset climate events (e.g., long term temperature rise), and rapid onset events (e.g., floods) by attributing those events to climate change and measuring how frequent or likely those events became due to climate change. The development of robust methods for loss and damage will be very useful for climate change negotiations.

Adaptation and resilience work will need interdisciplinary (all branches of physical and social sciences) and trans-disciplinary partnerships (among academia, civil society and private sector/industry). This will also require sustained efforts towards knowledge dissemination to users of climate monitoring and modelling datasets, especially governments, civil society and industry, to provide them with user-friendly data and training them to use it for improving adaptation and resilience. There is thus a need to create a few pan-India **Climate and Health Observatories.**

Given the diversity of information sources on models, impacts and solutions there is an imminent need to consolidate this for the health sector to increase climate preparedness and minimise population-level health impacts. A few pan-India Climate and Health Observatories are envisaged as a partnership between the Office of the PSA, the India Meteorological Department, the Indian Space Research Organisation, the Indian Council of Medical Research, the National Centre for Disease Control, academic institutions of repute (with specialisations in Public Health, Atmospheric Sciences, Environmental Sciences, Data Sciences and Public Policy), WHO - SEARO and other relevant organisations. Such observatories are in operation in different regions globally and a framework is being suggested based on the European Observatory for Climate and Health (https://climate-adapt.eea.europa.eu/en/observatory).

Partner organisations will jointly maintain a collaborator portal to provide concrete in-kind contributions and activities that contribute to the strategic objectives of the Observatories (outlined below). The partners will actively participate in routine network meetings to take stock of the portal's outputs and suggest the most efficient ways of improving upon them to resonate with stakeholder requirements. All partners will assume collective responsibility for the deliverables and maintain high levels of accountability.

Strategic aims and objectives

The primary aim of the Observatories will be to serve as a single-stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. Specific objectives will include:

1. *Creation of reliable indicators to monitor key climate-related health risks, impacts and adaptive responses* (such as distribution, intensity, frequency of climate hazards relevant to health, exposure profiles for populations to specific hazards, vulnerability of populations and health systems to climate hazards, adaptive capacities and resilience of populations and health systems).
2. *Enabling national and sub-national health policies and systems to integrate across multiple adaptation strategies* (by supporting networking, collaboration and knowledge exchange among partners on health risk estimates generated at district, state and national levels; supporting climate-aware policy development, health system preparedness and health sector planning via integration of lessons learnt from a comprehensive compilation of regional adaptation reports).
3. *Building greater capacities for public health authorities to anticipate and prevent climate-related threats to health in a timely manner* (by developing disease forecasting models and integrating them with climate-related health emergency events to enable timely detection and response to climate sensitive health risks).
4. *Creating greater levels of climate literacy among stakeholders* (by conducting professional development modules on climate for the health sector and health for the other actors in the climate sector, including urban planners, civil engineers and disaster management personnel; by creating and sharing repositories of evidence-based, efficient, effective and inclusive adaptation solutions.

5.8.1. A prioritised action plan for the Science of climate change adaptation and resilience

Since the ongoing climate change seems to be irreversible for at least a few hundred years, it is necessary to invest in researching the best adaptation and resilience methods and techniques to protect humans, livestock and the environment from the adversity of climate change. The agriculture, fishery and livestock sectors are already being affected by the adversities of climate change.

In Phase I, it is proposed to concentrate on designing and executing projects to quantify the impact of climate change on agriculture, fishery, livestock and health and develop models to understand the impacts due to future climate. This will also include the development of methodologies for quantifying loss and damage from both slow-onset climate events (e.g., long-term temperature rise), and rapid-onset events (e.g., floods).

Phase II will concentrate on projects to make the agricultural sector resilient to climate change by developing new agricultural varieties that can withstand high temperatures and other adversities of climate change. ICAR in collaboration with agricultural universities and research institutions will design and execute projects in that direction and conduct field trials and production in Phase III. ICAR will take up similar research projects in collaboration with fishery and dairy research institutions and universities to identify and promote the species that can withstand the adversities of climate change.

On-going research on adaptation, resilience methods and technologies can be simultaneously integrated with climate modelling and health risk assessment efforts to create a few pan-India

Climate and Health Observatories to assist on-going integration across sectoral actions for climate and health. We propose the integration of available surveillance information across Government departments to generate indicators that can be used for monitoring and evaluation of climate actions. While there is no primary research envisaged for the creation of the Observatories, multiple outputs from various research exercises are expected to be integrated via the Observatory portal/s and participating collaborating partners.

Table 5.8.1: Science of Climate Change Adaptation and Resilience: a 3-Phase Plan

S. No.	**Type of Activities**	**Phase-I**		**Phase-II**		**Phase-III**		**Total**	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
1.	Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc.	5	10.00	10	20.00	30	35.00	45	65.00
2.	Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods)	5	7.00	10	15.00	20	35.00	35	57.00
3.	Projects to develop indicators, metrics and frameworks for implementing and measuring effectiveness of adaptation in reducing climate risks	2	2.00	2	2.00	1	1.00	5	5.00
4.	Projects to develop models and scenarios for measuring and quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits	2	2.00	2	2.00	1	1.00	5	5.00
5.	Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative	2	10.00	2	10.00	2	10.00	6	30.00

	source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks.								

Chapter 6: Funding and Management of Mega Science Projects on Climate Change Research

6.1. Funding and management of Mega Science Projects

In India, the evolution of MSPs' funding and management structures started with the India-CERN engagement in the mid-1990s. It evolved as India got involved in other MSPs, both nationally and internationally. While there are some fine differences amongst the structures of different projects dictated by their particular needs and how they are internationally structured, one can also easily discern some broad common features among those structures. Very briefly, those are:

a) Each MSP is a pan-India collaboration with an identified project leader, with appropriate connections to the international project as applicable.
b) Each MSP is approved and overseen during its implementation by a high-level apex committee co-chaired by the chiefs of all the funding agencies with scientific experts, financial authorities and other concerned agency officials as members.
c) Each MSP has a high-level scientific expert committee overseeing the project's scientific and technical aspects and the Apex committee considers its recommendations.

Overall, these structures have served well, and the growing number of MSPs in the country can be taken as a good indicator. However, over time, and with the increasing number and variety of MSPs, the scientific community feels that there is a need for minor modifications in the structures and processes to address the following issues:

i. If the concerned scientific community is inclined to launch an MSP or participate in an international collaboration, it needs a window in the government to approach.
ii. Funding cycles are often much shorter than the appropriate activity period in the project life cycle (design phase, construction phase, operation and maintenance phase, etc.), leading to funding uncertainties during the project life cycle and the consequent undesirable effects on project implementation.
iii. The process of newer groups/investigators joining a particular project, which is natural in long-term projects like these, often takes time.
iv. While periodic changes in the membership of the scientific expert committee overseeing the MSP are unavoidable and desirable, some essential continuity in

the functioning and membership of the scientific expert committee is also crucial to avoid any information gap.

v. Involvement of international experts in various expert committees has largely been absent. They may play a valuable complementary role.

Keeping all these in view, the climate change research community would like to suggest the following plan for funding and management structures for MSPs. Different stages are presented separately.

6.2. Statement of Intent stage

At the outset, it must be mentioned that the need to get into a project, either nationally or internationally, is driven by the emerging contours of the underlying science and/or technology. Nationally, the concerned scientific community (from now on to be identified as the Climate Research (CR) community for this Report) may get into an MSP as a natural extension of an existing project or to meet an essential national developmental need. The national CR community may also like to join hands with the international community to offer ideas and solutions for internationally competitive scientific research or develop new technologies for observations, mitigation, adaptation, etc. The international community can be invited through calls for proposals or bilateral/multilateral collaborations. There are occasions when this can also happen through government channels. As expected, the first step towards the possibility of undertaking such projects nationally or internationally is a discussion among the CR community in the country. It is only when the national CR community, after intense debate, is convinced that there is good scientific and/or technological benefit from the project and the manpower and funding requirements are within reach that it will decide to make a Statement of Intent (SOI) for the project. We suggest adopting the following mechanism to impart some structure to this process against its natural amorphous background.

Since there is no organized platform, like the DAE Nuclear Physics Symposium in the case of Nuclear Physics, to discuss all CR-related topics, a platform may be formed to facilitate in-depth discussions on all related issues. The community may take stock of the ongoing CR Projects and decide on the new MSP that needs to be taken up, form a group of scientists to lead the project and ask them to formulate an SOI for the project. The SOI may, among other things, contain the scientific/technological need, the interested institutions/groups, a contact scientist and his deputies, the time frame for the project, likely funding requirements and likely funding agencies in the country.

The CR community suggests creating a common CR Mega Science Nodal Unit (MSNU) in a suitable agency. The SOI should be submitted to this MSNU for initial evaluation. The MSNU may get the SOI evaluated by an appropriate body of national and international experts, and if found suitable, give the go-ahead for the proposal, in principle, and decide on the funding agencies, including the Lead Agency. In such a case, the MSNU will forward the SOI to the Lead Agency and ask the contact scientist to submit a more detailed proposal based on the requirements of the Lead Agency.

After the MSNU gives the initial go-ahead, the theatre of activities will shift to the Lead Agency and other funding agencies.

6.3. Funding stages

The scientists interested in the MSP will then submit a proposal to a Project Evaluation Committee (PEC) constituted by the funding agency/ies under the chairmanship of an expert scientist in the field. The proposals thus evaluated by the PEC will be submitted to the funding agency for further processing and funding. Generally, the funding proposal will be for one of the following three types of MSPs:

i. MSPs consisting of research project/s to identify and quantify the changes in the Earth System due to climate change, understand and quantify the impacts on humans, the environment, weather, agriculture, water cycle, fisheries, etc. This group of projects can also include making long-term observations, analysing past data, etc.
ii. MSPs consisting of project/s to develop technologies/instruments for automated observations, satellite-based measurements, mitigation of the impacts of climate change, adaptive mechanisms, etc.
iii. MSPs consisting of project/s to develop numerical models to simulate the future climate under perceived changes and issue advisories to facilitate governmental and societal policies.

6.4. Project evaluation processes

Each project proposal must be considered for funding based on its scientific and technical merit. The CR community feels that it should be done by the PEC, which comprises eminent national and international experts.

Given that these are primarily inter-agency projects, it will be important that the final funding decision is taken by an Inter-Agency Committee co-chaired by the chiefs of the participating agencies, their financial authorities and senior officials, the chairperson of the PEC and some other scientific and technical experts.

6.5. Project implementation processes

In funding agencies

Given that such projects are very long-term projects and continuity in management systems is of paramount importance, it is suggested that during implementation, the Inter-Agency Committee that decides on the funding of the project should serve as the Apex Inter-Agency Project Management Board (PMB) co-chaired by the chiefs of the participating agencies. As it will be difficult for the same PMB/Committees to continue without change in such long-term projects, the changes in PMB/Committees should not exceed 1/3rd in a year to ensure continuity of members so that these bodies seamlessly carry forward project memory.

[Note: If the project is huge, a smaller Empowered Board (EB) consisting of senior agency representatives, financial authorities, and some scientific and technical experts could also be formed with clear delegation of powers to take appropriate decisions to realise the project within the approved cost and timeline.]

PMB will lay down the mechanism for periodic reporting and monitoring of project deliverables.

PMB will also lay down transparent guidelines for adding new groups during implementation. It is neither feasible nor desirable that the number of participating groups does not grow during the long life-cycle of these projects.

In participating institutions

Management of the project at the investigators' institutions has, by now, acquired a canonical structure in the country, and it is suggested that the same may be continued. Each project has a Lead Scientist (called by various names ─ Project Director, Programme Director, Project Leader, etc.) who is responsible for implementing the project. In all cases, the Lead Scientist is to be either identified in the Project Proposal itself or appointed by the PMB if proposals from multiple institutions are merged at the evaluation stage to achieve higher productivity or for ease of implementation or effective sharing of resources.

As mentioned in the approved project document, each participating institution has a PI and co-PI of the project. It is suggested that the PMB should approve any subsequent change to this.

6.6. Funding cycles and fund-flow issues

Regarding fund flow to the participating institutions, two models have been followed:

(i) The agencies sanction funds directly to only one or few nodal institutions, and they, in turn, send the funds to other participating institutions for carrying out their share of work; or
(ii) The agencies sanction funds directly to each participating institution.

While the first model may appear easier from the agencies' point of view, it puts enormous accounting load on the nodal institutions. Also, their accounts and audit systems must be willing to accept the financial processes of other institutions and the Statements of Expenditure and Utilization Certificates signed by them. Finally, the fundamental question is whether one grantee institution can disburse its grants to other institutions. This is not normally permitted as per financial rules, and, in effect, the nodal institution takes the onus of spending these funds in several other participating institutions.

In the second model, each participating institution functions as a grantee institution and submits a Statement of Expenditure and Utilization Certificate directly to the funding agency.

From the point of view of fiscal rectitude, it is suggested that while fund distribution etc., should be decided by the PMB on the recommendations of the PEC, the second model of direct fund flow from agencies to each participating institution may be followed. This may help avoid subsequent audit issues.

Funding cycles

It is realized that the Government funding cycle is 5-year long; it used to be the Plan Period, which has now been replaced by and aligned with the Finance Commission Period.

Many of the MSPs in the past had durations of 5 years; even then they were not always aligned with the Plan Periods or the Finance Commission Periods. While such projects continued over several 5-year periods because of their long-term nature, the fund sanctioning in tranches of 5 years has led to operational difficulties and uncertainties.

Therefore, it is suggested that funds should be sanctioned for the total period of a specific activity cycle or phase of a project. This will also help the Funding Agencies to keep track of their committed liabilities and make appropriate projections for every Finance Commission Period.

6.7. Prioritisation of projects for funding

The proposals for MSPs that may come up for funding can be classified into the following four categories.

(i) MSPs consisting of proposals to generate climate quality data and quantify the climatic parameters, especially the GHG emissions, such that their outcomes are directly helpful to the government for policymaking and international negotiations in addition to promoting basic research in climate change.

(ii) MSPs consisting of proposals whose outcomes suggest sustainable, economical and easily replicable adaptive measures to mitigate the effects of climate change. They include water conservation and management solutions, heat-resistant crops, salt-resistant crops, maintenance of fishery stocks, etc.

(iii) MSPs consisting of proposals for developing technologies to observe climate variables, adaptation, mitigation (for example, carbon capture/sequestration), etc.

(iv) MSPs consisting of proposals for understanding the science of climate change and its impacts on various components of the Earth's environment and its inhabitants, especially humans.

When funds are limited, and it is not possible to fund all qualified proposals in terms of scientific and technological soundness, the necessity to address the objectives, the correctness of methodology, the reasonableness of timelines and the usefulness of the results and outcomes, PEC may prioritize the selection of proposals based on the direct applicability and necessity of the outcomes from the project to understand or quantify or adapt or mitigate climate change.

6.8. Follow-up on project spin-offs

Each such MSP usually leads to some important and futuristic technological spin-offs that can be of great national value if developed further. Further development of these technologies for niche applications would require separate funding. At present, there is no mechanism through which such projects can be supported, even though the initial funding required is small. It is suggested that the MSNU also receive such projects for initial evaluation and further directions about the possible sources of their funding.

Acknowledgements

The preparation of this Report would not have been possible without the whole-hearted support of the Climate Science community in the country. The Working Group deliberated upon, and developed, the document over a long period, synthesizing all aspects of Climate Research, and highlighting the need and a prioritized plan for mega science activities to further enhance the overall national R&D profile of this important area of research. An early draft of this document was circulated to a large number of researchers (approximately 3,200) nationwide for their feedback. Sixty-eight of them sent their comments. The draft was further reviewed by a group of thirty-five national as well as international experts, who made valuable suggestions in person at an online meeting and/or through e-mails. All these valuable comments greatly improved the content and structure of the document. We sincerely thank them for their constructive inputs and sustained interest.

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Appendix – Prioritized Action Plan and Budgetary Requirements

A PRIORITIZED LANDSCAPE

Phase-I			
Modest Growth Scenario		**Aspirational Growth Scenario**	
Required Funding	**Rs. crore**	**Required Funding**	**Rs. crore**
Observational Networks		**Observational Networks**	
(1) Climate Observatories Network		**(1) Climate Observatories Network**	
• AWSs (15 Nos.)	1.05	• AWSs (30 Nos.)	2.10
• Radiosonde Ascent Facility (10 Nos.)	6.00	• Radiosonde Ascent Facility (15 Nos.)	12.00
• Moored Met-Ocean Data Buoys (3 Nos.)	8.00	• Moored Met-Ocean Data Buoys (5 Nos.)	15.00
• Ocean Gliders (3 Nos.)	10.00	• Ocean Gliders (5 Nos.)	20.00
• Argo Floats (12 Nos.)	4.00	• Argo Floats (20 Nos.)	6.80
(2) GHG Emission Observatories (10 Nos.)	12.00	(2) GHG Emission Observatories (20 Nos.)	16.00
(3) Glacier Observatories (5 Nos.)	12.00	(3) Glacier Observatories (10 Nos.)	15.00
(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (15 Nos.)	2.50	(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (30 Nos.)	5.00
Indigenous Development of Sensors and Instruments		**Indigenous Development of Sensors and Instruments**	
(1) AWSs (6 Nos.)	2.50	(1) AWSs (12 Nos.)	4.20
(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (5 Nos.)	3.00	(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (10 Nos.)	6.00
(3) Radiosondes (7 Nos.)	7.50	(3) Radiosondes (15 Nos.)	15.00

(4) Profiling Floats with T, S and Chlorophyll sensors (5 Nos.)	4.00	(4) Profiling Floats with T, S and Chlorophyll sensors (10 Nos.)	7.50
(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (2 Nos.)	1.05	(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (5 Nos.)	1.75
(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (10 Nos.)	0.50	(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (20 Nos.)	1.00
(7) Micro Pulse LIDAR with Dual Polarisation Capability (2 Nos.)	3.00	(7) Micro Pulse LIDAR with Dual Polarisation Capability (5 Nos.)	7.50
(8) All Sky Imagers for Cloud Fraction (10 Nos.)	0.50	(8) All Sky Imagers for Cloud Fraction (20 Nos.)	1.00
(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (2 Nos.)	1.00	(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (5 Nos.)	2.00
(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (5 Nos.)	1.75	(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (10 Nos.)	3.50
(11)Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (2 Nos.)	1.00	(11)Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (5 Nos.)	5.00
(12) Lower Atmospheric Wind Profilers (2 Nos.)	7.00	(12) Lower Atmospheric Wind Profilers (5 Nos.)	15.00
Remote Sensing and Satellite-based Monitoring		**Remote Sensing and Satellite-based Monitoring**	
(Detailed Sensor System Studies and Instrument Design)		*(Detailed Sensor System Studies and Instrument Design)*	
(1) GHG and Aerosols Monitoring Mission	2.50	(1) GHG and Aerosols Monitoring Mission	5.00
(2) Hydrology Constellation	2.50	(2) Hydrology Constellation	5.00
(3) Cloud and Precipitation Mission	2.50	(3) Cloud and Precipitation Mission	5.00
(4) Himalayan Climate Mission	2.50	(4) Himalayan Climate Mission	5.00
(5) Space-based Scatterometer Indian Mission	2.50	(5) Space-based Scatterometer Indian Mission	5.00
(Improved Sensor Resolutions)		*(Improved Sensor Resolutions)*	

(6) Continuity Missions from Geostationary Platform	2.50	(6) Continuity Missions from Geostationary Platform	5.00
Development of Indigenous India-specific Climate Models		**Development of Indigenous India-specific Climate Models**	
(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (5 Nos.)	2.50	(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (10 Nos.)	5.00
(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (Nil)	-	(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (Nil)	-
(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (Nil)	-	(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (Nil)	-
Improving the Existing Models		**Improving the Existing Models**	
(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (5 Nos.)	2.50	(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (10 Nos.)	5.00
(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (Nil)	-	(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (Nil)	-
(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (Nil)	-	(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (Nil)	-
(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (Nil)	-	(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (Nil)	-
Thematic Mega-Campaigns/Experiments		**Thematic Mega Campaigns/Experiments**	
(1) For studying impact of radiatively active atmospheric constituents on climate variables and air quality (No. of campaigns/experiments - 3)	6.00	(1) For studying impact of radiatively active atmospheric constituents on climate variables and air quality (No. of campaigns/experiments - 10)	10.00

(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 1)	3.00	(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 2)	5.00
(3) For studying warming of oceans, deoxygenation, acidification and their effects on life underwater (No. of campaigns/experiments - 5)	8.00	(3) For studying warming of oceans, deoxygenation, acidification and their effects on life underwater (No. of campaigns/experiments -10)	17.00
(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 3)	6.00	(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 5)	10.00
(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - Nil)	-	(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - Nil)	-
Carbon-neutrality Research		**Carbon-neutrality Research**	
(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (3 Nos.)	7.00	(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (8 Nos.)	15.00
Science of Climate Change Adaptation and Resilience		**Science of Climate Change Adaptation and Resilience**	
(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (3 Nos.)	6.00	(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (5 Nos.)	10.00
(2) Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods). (2 Nos.)	3.00	(2) Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods). (5 Nos.)	7.00
(3) Projects to develop indicators, metrics and frameworks for		(3) Projects to develop indicators, metrics and frameworks for	

implementing and measuring effectiveness of adaptation in reducing climate risks. (1 No.)	1.00	implementing and measuring effectiveness of adaptation in reducing climate risks. (2 Nos.)	2.00
(4) Projects to develop models and scenarios for measuring and quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (1 No.)	1.00	(4) Projects to develop models and scenarios for measuring and quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (2 Nos.)	2.00
(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (1 No.)	5.00	(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (2 Nos.)	10.00

Phase-II			
Modest Growth Scenario		**Aspirational Growth Scenario**	
Required Funding	**Rs. crore**	**Required Funding**	**Rs. crore**
Observational Networks		**Observational Networks**	
(1) Climate Observatories Network		**(1) Climate Observatories Network**	
• AWSs (15 Nos.)	1.05	• AWSs (30 Nos.)	2.10
• Radiosonde Ascent Facility (5 Nos.)	4.00	• Radiosonde Ascent Facility (10 Nos.)	8.00
• Moored Met-Ocean Data Buoys (3 Nos.)	9.00	• Moored Met-Ocean Data Buoys (3 Nos.)	9.00
• Ocean Gliders (3 Nos.)	12.00	• Ocean Gliders (3 Nos.)	12.00
• Argo Floats (12 Nos.)	4.00	• Argo Floats (20 Nos.)	6.80
(2) GHG Emission Observatories (5 Nos.)	4.00	(2) GHG Emission Observatories (10 Nos.)	8.00
(3) Glacier Observatories (3 Nos.)	4.00	(3) Glacier Observatories (5 Nos.)	7.50
(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (15 Nos.)	2.50	(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (25 Nos.)	5.00
Indigenous Development of Sensors and Instruments		**Indigenous Development of Sensors and Instruments**	
(1) AWSs (10 Nos.)	0.50	(1) AWSs (30 Nos.)	1.50
(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (10 Nos.)	5.00	(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (25 Nos.)	15.00
(3) Radiosondes (10 Nos.)	2.50	(3) Radiosondes (25 Nos.)	6.00
(4) Profiling Floats with T, S and Chlorophyll sensors (10 Nos.)	4.00	(4) Profiling Floats with T, S and Chlorophyll sensors (30 Nos.)	8.00
(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (5 Nos.)	2.50	(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (15 Nos.)	5.25

(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (25 Nos.)	1.50	(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (50 Nos.)	2.50
(7) Micro Pulse LIDAR with Dual Polarisation Capability (5 Nos.)	4.00	(7) Micro Pulse LIDAR with Dual Polarisation Capability (5 Nos.)	7.50
(8) All Sky Imagers for Cloud Fraction (25 Nos.)	1.50	(8) All Sky Imagers for Cloud Fraction (50 Nos.)	2.50
(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (5 Nos.)	2.00	(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (10 Nos.)	4.00
(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (10 Nos.)	3.75	(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (20 Nos.)	7.00
(11) Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (5 Nos.)	5.00	(11)Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (10 Nos.)	10.00
(12) Lower Atmospheric Wind Profilers (5 Nos.)	15.00	(12) Lower Atmospheric Wind Profilers (10 Nos.)	30.00
Remote Sensing and Satellite-based Monitoring		**Remote Sensing and Satellite-based Monitoring**	
(Fabrication, Development, Launch-related Infrastructure)		*(Fabrication, Development, Launch-related Infrastructure)*	
(1) GHG and Aerosols Monitoring Mission	10.00	(1) GHG and Aerosols Monitoring Mission	20.00
(2) Hydrology Constellation	15.00	(2) Hydrology Constellation	30.00
(3)Cloud and Precipitation Mission	10.00	(3)Cloud and Precipitation Mission	20.00
(4) Himalayan Climate Mission	15.00	(4) Himalayan Climate Mission	25.00
(5) Space-based Scatterometer Indian Mission	15.00	(5) Space-based Scatterometer Indian Mission	20.00
(6) Continuity Missions from Geostationary Platform	20.00	(6) Continuity Missions from Geostationary Platform	25.00
Development of Indigenous India-specific Climate Models		**Development of Indigenous India-specific Climate Models**	

(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (Nil)	-	(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (Nil)	-
(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (25 Nos.)	20.00	(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (50 Nos.)	30.00
(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (Nil)	-	(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (Nil)	-
Improving the Existing Models		**Improving the Existing Models**	
(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (Nil)	-	(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (Nil)	-
(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (25 Nos.)	15.00	(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (50 Nos.)	30.00
(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (Nil)	-	(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (Nil)	-
(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (Nil)	-	(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (Nil)	-
Thematic Mega-Campaigns/Experiments		**Thematic Mega-Campaigns/Experiments**	
(1) For studying impact of radiatively active atmospheric constituents on		(1) For studying impact of radiatively active atmospheric constituents on climate	

climate variables and air quality (No. of campaigns/experiments - 10)	10.00	variables and air quality (No. of campaigns/experiments - 15)	15.00
(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 1)	4.00	(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 3)	10.00
(3) For studying warming of oceans, deoxygenation, acidification and their effects on life underwater (No. of campaigns/experiments - 10)	15.00	(3) For studying warming of oceans, deoxygenation, acidification and their effects on life underwater (No. of campaigns/experiments -15)	25.00
(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 5)	10.00	(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 10)	20.00
(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - 6)	12.00	(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - 10)	20.00
Carbon-neutrality Research		**Carbon-neutrality Research**	
(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (2 Nos.)	10.00	(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (5 Nos.)	20.00
Science of Climate Change Adaptation and Resilience		**Science of Climate Change Adaptation and Resilience**	
(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (6 Nos.)	12.00	(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (10 Nos.)	20.00
(2) Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term		(2) Projects to develop methodologies for quantifying loss and damage from both	

temperature rise), and rapid onset events (e.g., floods). (5 Nos.)	7.50	slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods). (10 Nos.)	15.00
(3) Projects to develop indicators, metrics and frameworks for implementing and measuring effectiveness of adaptation in reducing climate risks. (1 No.)	1.00	(3) Projects to develop indicators, metrics and frameworks for implementing and measuring effectiveness of adaptation in reducing climate risks. (2 Nos.)	2.00
(4) Projects to develop models and scenarios for measuring and quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (1 No.)	1.00	(4) Projects to develop models and scenarios for measuring and quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (2 Nos.)	2.00
(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (1 No.)	5.00	(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (2 Nos.)	10.00

Phase-III			
Modest Growth Scenario		**Aspirational Growth Scenario**	
Required Funding	**Rs. crore**	**Required Funding**	**Rs. crore**
Observational Networks		**Observational Networks**	
(1) Climate Observatories Network		**(1) Climate Observatories Network**	
• AWSs (15 Nos.)	1.05	• AWSs (15 Nos.)	1.05
• Radiosonde Ascent Facility (5 Nos.)	4.00	• Radiosonde Ascent Facility (5 Nos.)	4.00
• Moored Met-Ocean Data Buoys (2 Nos.)	6.00	• Moored Met-Ocean Data Buoys (2 Nos.)	6.00
• Ocean Gliders (2 Nos.)	8.00	• Ocean Gliders (2 Nos.)	8.00
• Argo Floats (10 Nos.)	3.40	• Argo Floats (10 Nos.)	3.40
(2) GHG Emission Observatories (5 Nos.)	4.00	(2) GHG Emission Observatories (10 Nos.)	8.00
(3) Glacier Observatories (3 Nos.)	5.00	(3) Glacier Observatories (5 Nos.)	7.50
(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (10 Nos.)	2.50	(4) Aerosols and Short-Lived Climate Forcers (SLCFs) Observatories (20 Nos.)	5.00
Indigenous Development of Sensors and Instruments		**Indigenous Development of Sensors and Instruments**	
(1) AWSs (30 Nos.)	1.50	(1) AWSs (60 Nos.)	3.00
(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (15 Nos.)	15.00	(2) Aerosol Spectral Optical Depths, Single Scattering Albedo and Size Distribution Measuring Instruments (50 Nos.)	30.00
(3) Radiosondes (25 Nos.)	5.00	(3) Radiosondes (50 Nos.)	8.00
(4) Profiling Floats with T, S and Chlorophyll sensors (30 Nos.)	5.00	(4) Profiling Floats with T, S and Chlorophyll sensors (60 Nos.)	10.00
(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (15 Nos.)	5.50	(5) Atmospheric Boundary Layer Fluxes (Sensible and Latent Heat Flux) Fast Response Sensors for Vertical Wind, Temperature and Humidity (25 Nos.)	8.75
(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (25 Nos.)	1.50	(6) Radiation Sensors (SW & LW, Incoming and Outgoing) (50 Nos.)	2.50

(7) Micro Pulse LIDAR with Dual Polarisation Capability (5 Nos.)	7.50	(7) Micro Pulse LIDAR with Dual Polarisation Capability (10 Nos.)	15.00
(8) All Sky Imagers for Cloud Fraction (25 Nos.)	1.50	(8) All Sky Imagers for Cloud Fraction (50 Nos.)	2.50
(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (8 Nos.)	3.00	(9) Precipitation Measurements (Microwave Rain RADAR & Disdrometer/Laser Precipitation Monitor) (15 Nos.)	6.00
(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (10 Nos.)	3.75	(10) Set of Trace Gas Analysers (O_3, NO_x, CO) with Calibrator (20 Nos.)	7.00
(11)Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (5 Nos.)	5.00	(11)Eddy Covariance Flux Towers (50 m) for Gas (CO_2, CH_4, Water Vapour) Exchange Estimations (10 Nos.)	10.00
(12) Lower Atmospheric Wind Profilers (10 Nos.)	30.00	(12) Lower Atmospheric Wind Profilers (15 Nos.)	45.00
Remote Sensing and Satellite-based Monitoring		**Remote Sensing and Satellite-based Monitoring**	
(Analysis-ready Data Products, Dissemination, Climate Research Studies/ projects undertaken by academia and researcher community/ Policy Framework and Implementation Plans)		*(Analysis-ready Data Products, Dissemination, Climate Research Studies/ projects undertaken by academia and researcher community/ Policy Framework and Implementation Plans)*	
(1) GHG and Aerosols Monitoring Mission	10.00	(1) GHG and Aerosols Monitoring Mission	10.00
(2) Hydrology Constellation	10.00	(2) Hydrology Constellation	10.00
(3)Cloud and Precipitation Mission	10.00	(3)Cloud and Precipitation Mission	10.00
(4) Himalayan Climate Mission	10.00	(4) Himalayan Climate Mission	10.00
(5) Space-based Scatterometer Indian Mission	10.00	(5) Space-based Scatterometer Indian Mission	10.00
(6) Continuity Missions from Geostationary Platform	10.00	(6) Continuity Missions from Geostationary Platform	10.00
Development of Indigenous India-specific Climate Models		**Development of Indigenous India-specific Climate Models**	
(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (Nil)	-	(1) Workshops and Brainstorming Meetings for preparation of the Flow Diagram (Nil)	-

(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (Nil)	-	(2) Proposals for the development of different components of the Model; evaluation of the schemes, algorithms, etc. developed (Nil)	-
(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (15 Nos.)	20.00	(3) Proposals for development of codes for individual components, testing and integration, and implementation of the Model (24 Nos.)	30.00
Improving the Existing Models		**Improving the Existing Models**	
(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (Nil)	-	(1) Workshops and Brainstorming Meetings for incorporation of new Earth System components (Nil)	-
(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (Nil)	-	(2) Proposals for the incorporation of new Earth System Components, and Community Model Development (Nil)	-
(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (6 Nos.)	20.00	(3) Proposals for development of GPU-based Computing and Hybrid Models (Physics + ML based) (10 Nos.)	30.00
(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (5 Nos.)	8.00	(4) Proposals for customisation of climate model outputs for various sectorial applications including downscaling at local and regional scale (10 Nos.)	10.00
Thematic Mega-Campaigns/Experiments		**Thematic Mega-Campaigns/Experiments**	
(1) For studying impact of radiatively active atmospheric constituents on climate variables and air quality (No. of campaigns/experiments - 10)	10.00	(1) For studying impact of radiatively active atmospheric constituents on climate variables and air quality (No. of campaigns/experiments - 20)	20.00
(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 2)	7.50	(2) For studying interaction between changing climate and hydrological systems (No. of campaigns/experiments - 4)	15.00
(3) For studying warming of oceans, deoxygenation, acidification and their effects on		(3) For studying warming of oceans, deoxygenation, acidification and their effects on	

life underwater (No. of campaigns/experiments - 10)	15.00	life underwater (No. of campaigns/experiments -20)	40.00
(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 5)	10.00	(4) For studying anthropogenic influence on the Himalayan Cryosphere and its climate impacts assessment (No. of campaigns/experiments - 10)	20.00
(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - 6)	12.00	(5) For studying urban heat island effects and regional climate impact assessment and mitigation (No. of long-term campaign mode experiments at urban stations in India - 10)	20.00
Carbon-neutrality Research		**Carbon-neutrality Research**	
(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (6 Nos.)	20.00	(1) Projects on carbon sequestration through absorption of atmospheric carbon utilizing natural processes and development of technologies (10 Nos.)	35.00
Science of Climate Change Adaptation and Resilience		**Science of Climate Change Adaptation and Resilience**	
(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (15 Nos.)	18.00	(1) Projects to quantify the impacts of climate change on environment, agriculture, water management, health, etc. (30 Nos.)	35.00
(2) Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods). (10 Nos.)	18.00	(2) Projects to develop methodologies for quantifying loss and damage from both slow onset climate events (e.g., long-term temperature rise), and rapid onset events (e.g., floods). (20 Nos.)	35.00
(3) Projects to develop indicators, metrics and frameworks for implementing and measuring effectiveness of adaptation in reducing climate risks. (1 No.)	1.00	(3) Projects to develop indicators, metrics and frameworks for implementing and measuring effectiveness of adaptation in reducing climate risks. (1 No.)	1.00
(4) Projects to develop models and scenarios for measuring and		(4) Projects to develop models and scenarios for measuring and	

quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (1 No.)	1.00	quantifying feasibility and effectiveness of future adaptation (at higher global warming levels) and to develop predictive abilities to know when limits to adaptations are being reached because of hard physical limits. (1 No.)	1.00
(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (1 No.)	7.00	(5) Projects to establish pan-India Climate and Health Observatories to serve as a single stop and authoritative source of actionable knowledge on the past, current and projected climate change risks to health for both rural and urban populations, as well as on specific policies and actions that are in operation to address such risks. (2 Nos.)	10.00

Notes:

1. The afore-listed projects on observations have considered the existing networks for data collection on climate variables. These proposals are based on the requirement to build climate-specific observations with well-calibrated and standardized sensors/instruments to provide accurate climate data over the inhomogeneous spans of the country. Observations are the backbone to monitor and quantify climate changes, understand the science behind the climate change, its impacts on weather, environment, society, resources, economy, etc., to plan and implement resilience and adaptation strategies, and offer policy guidance.

2. The modelling projects aim to better understand the observed changes in the climate variables and impacts, and the dynamics and processes involved, for making more reliable predictions and projections essential for disaster management and mitigation, planning and policy making.

3. To know more about the requirements of these projects to improve the climate research in the country from observations to resilience and adaptation, one may specifically refer to the following portions of the Report —

> *Chapter 2: Physical Science Basis; Sections 2.2, 2.3 and 2.5; for observational networks and remote sensing and satellite-based monitoring.*
>
> *Chapter 3: Societal Impacts of Climate Change; Sections 3.3 and 3.4; for projects related to adaptation and resilience.*

Chapter 4: Policy Implications, Human Resource Development/Capacity Building and Transition/Communication; Sections 4.1, 4.3, 4.6 and 4.7; for projects on capacity development.

Chapter 5: Mega Science Projects for Climate Research; Sections 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 and their subsections 5.1.1., 5.2.1, 5.3.1, 5.4.1, 5.5.1, 5.6.1, 5.7.1, 5.8.1; for projects on observational networks, indigenous development of sensors, remote sensing and satellite-based monitoring, development and improvements in climate models, thematic mega-campaigns, carbon neutrality research, etc.

4. The "Aspirational Growth Scenario" above presents the level of Climate Research activities in the country, and the required resources for the same, that the Indian Climate Research Community aspires to reach till 2035 based on the assessment presented in this Report. This obviously matches with the projections made in Chapter 5. The community, however, has also presented a "Modest Growth Scenario" which should be reached, at the very least, to maintain a healthy Climate Research ecosystem in the country, should there be unforeseen constraints on resources.

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