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M.N. Rajeevan
Shailesh Nayak *Editors*

Observed Climate Variability and Change over the Indian Region

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Foreword

India is one of the few countries in the tropics that have a long record of observations that are necessary to understand tropical climate variability. These long records are essential to understand changes in climate that occur over both short and long time scales. During the past 50 years, there has been a concern about the influence of human beings on the earth's climate. Climate can change over a long period on account of natural causes. Major ice ages have occurred on our Earth every 100,000 years during the past few million years. These were caused by small changes in the Earth's orbital parameters. In the twentieth century, the changes in climate have occurred both on account of human activities and natural variability. To unravel the relative contribution of anthropogenic and natural causes is a great challenge. We need to differentiate between modes of natural variability from changes induced by human actions.

This book documents the changes in climate that have occurred in India during the past 150 years. There is a detailed discussion on the variability of temperature, humidity and rainfall in the India. An exhaustive study of extreme events such as droughts, floods, heat and cold waves has been made. The variations in sea surface temperature in seas around India influence the Indian monsoon. Hence, one chapter is devoted to the documentation of the variability of sea surface temperature in this region. One of the important consequences of global warming is the rise in sea level and hence the rise in sea level in various coastal stations in India has been discussed. Global warming has caused the retreat of many glaciers in the Himalayas and these changes have been delineated comprehensively. Air pollution has become an important issue in India today. Hence, there is a thorough discussion on the changes in aerosols, trace gases and ozone and their impact on radiation budget at the surface. The changes that occurred in the monsoon in the past have been highlighted through proxy indicators such as tree rings and stalagmites. There is a

discussion on change in regional climate in the future under various scenarios. This book will serve as an excellent reference book for those who want to understand climate variability and change in India. I congratulate the editors and the authors for bringing out such an excellent compilation.

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Preface

The Earth's climate system includes the land surface, atmosphere, rivers and oceans and cryosphere. Many aspects of the global climate are changing as evident in the long-term observations from the top of the atmosphere to the depths of the oceans. All these observations provide the unambiguous evidence of global warming. However, the changes in climate are not expected to be uniform across the Earth. There are significant regional variations in terms of magnitude of changes in the climate system. In some cases, regional changes may not necessarily follow the global trends. Climate change impacts are already evident and are expected to become increasingly disruptive across the globe. However, the nature of the impacts and associated vulnerability varies geographically.

To make an assessment of regional climate change and the possible impacts on agriculture, water resources, health, etc., it is important to have a clear comprehensive view on the observed climate variability and change over the region. There are many research studies documenting changes in the climate system over the Indian region using different instrumental and re-analysis data sets. However, these studies used data sets of varying lengths and the results differ both quantitatively and qualitatively. There is also a strong evidence of multi-decadal variability in the climate system over the region. Therefore, it is important to make a comprehensive assessment of the changes in the regional climate system using data sets of longer period and preferably for the common period.

This book compiles articles that review observed changes in the regional climate system. Using various long-term instrumental data sets starting from 1901, the contributing authors describe the observed changes in different components of the regional climate system, atmosphere, ocean and the cryosphere. The last chapter, however, deals with the future climate change scenarios over the region derived from various coupled climate models.

It is hoped that this book will immensely contribute in better understanding of the regional climate change and its possible attribution to natural and anthropogenic activities. The book may be used as reference material for research students and policymakers.

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M.N. Rajeevan
Shailesh Nayak

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Shailesh Nayak

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Editors and Contributors

About the Editors

Dr. Madhavan Nair Rajeevan is at present working as the Secretary, Ministry of Earth Sciences, Government of India at New Delhi. He has more than 30 years of research and operational experience in many aspects of Tropical Meteorology. His main research contributions include understanding monsoon variability and development of monsoon prediction models, understanding extreme weather events like heavy rainfall and heat waves and cloud–radiation interaction. He had served in many international expert panels of WMO/WCRP including as a member of the Asian-Australian Monsoon Panel. He briefly served as the High-Level Adviser to the Commission for Climatology, WMO. He is a Fellow of the Indian Academy of Sciences and National Academy of Sciences, India.

Dr. Shailesh Nayak is the former secretary, Ministry of Earth Sciences. He did his Ph.D. in Geology in 1980 from the M.S. University of Baroda, and specialized in Oceanography and remote sensing. Initially he has served in Indian Space Research Organization (ISRO) and worked on research areas of Coastal and Ocean processes and ocean-atmosphere interaction, coastal geomorphology, hazards. He has also served as the Director, Indian National Centre for Ocean Information Services, INCOIS, Hyderabad, where he has set up a state-of-the-art Early Warning System for Tsunami and Storm Surges in the Indian Ocean. He has been providing leadership for the programs related to science of climate change, weather services, polar science, ocean science and modelling, ocean survey, resources, and technology. He has published more than 100 papers in Journals, conferences & reports. He was honoured with an Honorary Doctorate of Science by Andhra University in 2011 and Assam University in 2013.

Contributors

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Dr. Hemant Boragaonkar is Senior Scientist at Indian Institute of Tropical Meteorology, Pune. He has more than three decades of vast experience in Long-Term Climate Change and Variability research with palaeoclimatic aspect, particularly with dendroclimatic approach. Over the Indian region Dr. Borgaonkar developed wide network of tree-ring chronologies of Himalayan conifers and teak (*Tectona grandis*) chronologies from central and peninsular India to understand the past climate changes since past 2000 years. Dendroclimatic studies of Himalayan conifers provide reliable reconstructions of pre-monsoon climate of the region since the past millennium. More than 40 research publications in national and

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Dr. M.G. Yadava is Scientist (SF) and in charge of the Radiocarbon Dating Laboratory in Geosciences Division at Physical Research Laboratory, Ahmedabad. His major research focus has been to reconstruct past climate through stable isotopes of oxygen, hydrogen and carbon ($\delta^{18}O$, δD and $\delta^{13}C$ respectively) and trace elements supported by radiocarbon and uranium–thorium-based chronology. He

has also used sedimentary deposits to find evidences of past climate change and soils to understand dynamics of organic carbon. Presently, he is involved in setting up a 1MeV Accelerator Mass Spectrometry (AMS) system for measuring ^{14}C, ^{10}Be and ^{26}Al in variety of natural samples.

Executive Summary

The summary on the variability and change of the regional climate system based on the 16 chapters in this book is as follows.

Rainfall

The analysis of rainfall over India is based on the quality-controlled district rainfall data for the period 1901–2010.

1. The all-India southwest monsoon rainfall does not show any long-term trend, but it exhibits significant multi-decadal variability.
2. However, there are significant regional trends in southwest monsoon rainfall. Monsoon rainfall in the meteorological subdivisions of Jharkhand, Chhattisgarh and Kerala have shown significant decreasing trends. However, monsoon rainfall over Gangetic West Bengal, West Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalaseema, Coastal Andhra Pradesh and North Interior Karnataka showed increasing trends.
3. Monsoon rainfall in the month of July has shown decreasing trends over most parts of central India. However, June and August rainfall has shown increasing trend over the central and southwestern parts of the country.
4. Northeast monsoon (October–December) over southeast peninsula does not show any significant trend, but shows multi-decadal variability.

Temperature

The analysis on surface air temperatures is made using gridded monthly temperature data for the period 1901–2010.

1. Annual mean, maximum and minimum temperatures averaged over the country as a whole showed significant warming trend of 0.60, 1.0 and 0.18 °C per 100

years respectively. The rate of warming trend in the annual mean temperatures since 1980s is much sharper, 0.2 °C per decade.
2. On the seasonal scale, the highest increasing trend is observed in the post-monsoon and winter seasons. Monsoon season shows the lowest increasing trend.
3. The warming is mostly confined to the northern, central and eastern/northeastern parts of the country. Peninsular India experienced the least warming.
4. The warming trend is observed in upper air temperatures also with significant warming trends at the lower tropospheric levels, viz. 850 hPa (1.5 km) and 700 hPa (3.1 km) levels.

Extreme Rainfall and Rainstorms

The analysis on extreme rainfall is made using daily gridded rainfall data for the period 1901–2010 and rainstorms based on daily gridded data for the period 1951–2015.

1. Frequency of very light rain and light to moderate rain events during the monsoon season has decreased over most of the country.
2. However, frequency of very heavy and extreme rainfall events over northern parts of the country has increased significantly. They also show multi-decadal variability, possibly associated with the tropical oceans, especially the equatorial Indian Ocean.
3. During the period, 1901–2010, heavy rainfall events (rainfall exceeding 15 cm in 24 hours) over northern parts of the country show an increasing trend of about 6 % per decade.
4. Frequency of rainstorms (weather systems with potential of causing large scale floods) has shown an increasing trend of 4 rainstorms in 65 years (1951–2015). Duration of rainstorms has shown a substantial increase of about 15 days during the same period.

Heat and Cold Waves

The analysis on heat and cold waves has been made based on daily temperature data of 103 stations for the period 1961–2010.

1. During the hot weather season (April–May–June), heat waves are experienced over the north, northwest, central, east India and northeast peninsula. Similarly, during the cold weather season (December–January–February), northern parts of the country including Jammu and Kashmir experience cold waves.
2. Significant decadal variation is observed in the frequency, spatial coverage and area of maximum frequency both in heat wave and cold wave.

3. Noticeable increase (decrease) in frequency of heat wave days is observed during the El Nino (La Nina) events. Exactly opposite association was observed in case of CW days.
4. Significant increasing (decreasing) trends in heat waves (cold waves) are observed during the hot (cold) weather season over most parts of the country.

Meteorological Droughts

The analysis on meteorological droughts is made using monthly rainfall data of the period 1901–2010 based on the Standardized Precipitation Index and Standard Precipitation Evapotranspiration Index (SPEI).

1. The all-India droughts are observed almost once in five years. More intense droughts are mainly observed over north and northwest India.
2. There is a significant increasing trend in the intensity and areal coverage of moderate droughts of various accumulated periods over India during the recent years, since 1950s. This increase could be also linked to warming of the equatorial Indian Ocean.

Tropical Cyclones and Monsoon Depressions

The analysis on tropical cyclones and monsoon depressions is made using the data of 1901–2010 period. A separate analysis during the satellite era (1961–2010) also has been made.

1. Over the north Indian Ocean, significant decreasing trends are observed in the frequencies of cyclonic disturbances and tropical cyclones during the southwest monsoon season.
2. Significant increasing trend in severe tropical cyclones is observed during the post-monsoon season (October–December).
3. During the satellite era (1961–2010), cyclonic disturbances, tropical cyclones and severe tropical cyclones over the north Indian ocean and Bay of Bengal show significant decreasing trends during the monsoon and post-monsoon seasons.
4. Monsoon low pressure systems forming over the Bay of Bengal during the monsoon season contribute significantly to the seasonal rainfall over the central parts of the country.

Total Cloud Cover

The analysis on cloud cover is made using 195 surface stations data for the period 1951–2010.

1. There is a general decrease in mean total cloud cover over most of India, but an increase in the Indo-Gangetic plains and northeast India.
2. The annual mean total cloud cover shows significant decreasing trend of 0.44 % per decade, mainly contributed by the monsoon season, where the declining rate is 0.93 % per decade.
3. Out of the total number of stations showing decreasing trends, 59, 38, 48, 58 and 33 % of the stations show significant decrease in total cloud cover for annual, winter, summer, monsoon and post monsoon seasons respectively.
4. There is a negative relationship between total cloud cover and diurnal temperature range suggesting decrease in cloud cover may be responsible for increase in diurnal temperature range.

Moisture Content

The analysis of surface moisture and soil moisture data has been made using the data of 1969–2012.

1. The all-India averaged specific humidity shows significant increasing trend during all the seasons, which is consistent with the surface warming trends.
2. The magnitude of seasonal trends in specific humidity is the highest in summer where it is increasing at the rate +0.32 g/Kg per decade and the lowest in monsoon season where the rate of increase is +0.20 g/Kg per decade.
3. The regional re-analysis data sets suggest an increase in atmospheric moisture content over the region during the same period.
4. Out of 27 stations considered for soil moisture analysis, 15 stations showed increasing trends in soil moisture.

Radiative Fluxes

The analysis on surface and top of the atmosphere radiative fluxes over the region is made using the data of the period 1981–2010.

1. The analysis of global irradiance data from India, from 1981 to 2006 showed a significant decreasing trend of 0.89 Wm^{-2} yr^{-1} under all sky conditions, called solar/global dimming.
2. The analysis of long-term global irradiance data from 1971 to 2010 showed that the declining trend of all-sky global irradiance over India as a whole was 0.6 $Wm^{-2}yr^{-1}$ during 1971–2000 and 0.2 $Wm^{-2}yr^{-1}$ during 2001–2010.
3. There is an indication of solar brightening after 2001, consistent with the decrease in total cloud cover.

Sea Surface Temperature, Ocean Circulation

The analysis on SST, Ocean Circulation and Ocean heat content has been made using the data of 1958–2015.

1. The tropical Indian Ocean is warming at a faster rate compared to other tropical oceans. The warming trend show a basin scale warming with peak warming in the central equatorial Indian Ocean (0.2 °C per decade).
2. There is a strengthening of mean westerly winds over the equatorial Indian Ocean in the recent years. There is also an evidence of strengthening of the mean eastward currents along the equator and westward currents in the equator.
3. The upper north Indian Ocean is gaining heat during the recent 60 years or so at an alarming rate, which is supported by the ocean circulation and dynamics.

Sea Level

The analysis on sea level has been made using data of varying lengths.

1. The sea level rise over the Arabian Sea and Bay of Bengal from the TOPEX/Poseidon altimeter observations depict that the rate over the Arabian Sea is about 0.5 mm/year to 3 mm/year and over the Bay of Bengal is 0.75 mm/year to 6 mm/year. The rise is of steric origin and are also driven by short-term climate variability.
2. The sea level rise in the Indian ocean over the last 60 years amounts to 1.5 mm/year, which is slightly less than the global average.
3. The AR5 projected sea level rise for all the scenarios with the highest emission scenario (RCP8.5) projecting sea-level rise in the range of 0.45–0.82 m for the late twenty-first century (average over 2081–2100) for the Indian Ocean

Glaciers and Snow Cover

The analysis of Glaciers and Snow cover has been made using different data sets of varying length.

1. The areal extent of glaciers in the Himalayas is estimated as 24,697 $\pm$ 3,260 Km^2.
2. Glacier retreat is estimated by numerous investigations and the mean loss for 83 glaciers for past four decades is estimated at 550 $\pm$ 419 m.
3. The retreat estimation has high uncertainty due to large variability in individual retreat.
4. An overall loss of area of 12.6 $\pm$ 7.5 % for 40 years from 1960 onwards.

5. The mass balance data is available for few glaciers and cumulative mass loss for the past 44 years is estimated as 20 ± 6 m.
6. The average snow cover in the Himalaya from 2000 to 2011 varied between ~ 0.3 and 0.03 million km^2. The average volume of snow is estimated at ~ 54.5, ~ 9.3 and ~ 14.5 billion cubic metres in the Indus, Ganga and Brahmaputra basins, respectively

Atmospheric Aerosol

The analysis of atmospheric aerosols is made using different data sets of varying lengths.

1. There is a phenomenal increase in aerosol loading over India. There is a statistically significant increasing trend in aerosol optical depth over India with a significant seasonal variability.
2. Seasonally, the rate of increase is consistently high during the dry months (from December to March). The trends are weak during the pre-monsoon and monsoon seasons.
3. There is a clear evidence of effect of anthropogenic activities in increase of aerosol loading.
4. Black carbon observations at a remote coastal location shows a decreasing trend, which is perceptible after 2004.

Ozone and Related Trace Gases

The analysis on atmospheric ozone has been done using different data sets of varying lengths.

1. There are indications of increasing total ozone at six sites over India except at Varanasi, where a decreasing trend was observed.
2. Ozonesonde data suggests at Pune, there are increasing trends of ozone at 9.7 % per year in the planetary boundary layer.
3. Surface ozone observations also show an increase of 1.45 % per year.

Paleoclimatic Records of Past Monsoons

The analysis on past monsoons is based on proxy data from different sources (tree rings and speleothems).

1. Monsoon fluctuations have been documented from teak trees in Kerala for the past 553 years.
2. The proxy data suggests that monsoon rainfall has been steadily increasing during the Holocene (the past 10000 years).