An overview of Climate change science over South Asia: Observations, Projections and Recent Advances

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Abstract

South Asia is among the most populous regions of the earth which houses fast developing economies. The unique geographical settings and socio-economic-demographic structure of the region makes it highly vulnerable to the risks posed by climate change as documented by several comprehensive scientific research reports. Human-induced climate change signatures have already been noted in the form of increasing extremes (e.g. cyclones, droughts, floods, heat waves, thunderstorms etc.), rising sea level and changing monsoon patterns over the region. Though considerable progress has been made towards understanding the science of climate change, regional climate change consequences are still not well understood and limited by sparse observational networks and inadequate knowledge of region-specific physical processes which often lead to large spread and uncertainties in model projections. Based on the available literature, the chapter highlights the past, present and future projections of climate over South Asia. Recent advances in observations and dedicated regional and earth system modeling activities over the region are also discussed alongside other emerging methodologies and tools which can lead to overall improvement in understanding of physical processes. We discuss the studies that have been carried out in the past and also the prospective gap areas that can be pursued in future through the use of a combined framework of modern observations-modeling-analysis techniques.

Keywords: South Asia, Climate change, Regional and global climate modeling, Remote sensing, Advanced statistical techniques

1. Introduction

The advent of climate change has become a significant global problem with far-reaching effects on electricity, food, water, natural resources, biodiversity, ecosystems, culture, and social well-being. Via a series of assessment papers, the United Nations Intergovernmental Panel on Climate Change (IPCC) has periodically presented the evidence of significant human impact on the climate system. Observations indicate substantial increase in the carbon footprint caused by anthropogenic activities which is unprecedented and stronger than the natural variations. Although climate change effects are seen worldwide, its devastating effects have varied across regions and nations. For example, surface temperature increase, sea-level rise, intense storm frequency and amplitude etc. were highly variable over various parts of the world (Stocker et al., 2013). Climate change effects on global scale are relatively well-understood and documented, while definitive regional assessments still remain grey (Flato et al. 2013). Sparse observational networks and inadequate knowledge of region-specific physical processes have generally been attributed to this limited understanding of regional climate change consequences.

The South Asian region, which includes countries of Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka (refer to Figure 1) has been assessed to be at increased risk of climate change consequences (Islam et al., 2009). The region lies majorly in the tropical latitudes of the northern hemisphere which is surrounded by the Indian Ocean in the south, by the Himalayan mountain range to the north, by the highlands of Baluchistan to the west, and by the north-south chain of mountains in the east. These distinct geographical settings in South Asia constrain the flow of air masses across the continent. Highly variable topography consisting of upland and lowland regions alongside rivers, gulfs and bays, greatly modulate the weather over the region. These regional features cause distinct climate conditions which are dominated by the monsoon season during boreal summer (Xue and Yanai 2005; Yadav and Singh 2015). Substantial precipitation over the western Himalayas is received through the Western Disturbances in the winter and early spring months. Rainfall and glaciers contribute significantly to the river inflows which irrigates the alluvial soils of the great river deltas and valleys. The region houses the largest delta with vast floodplain on the earth, i.e. the Bengal delta, apart from other significant river deltas. These deltas serve as major sources of freshwater supply and freshwater ecosystems. Such favourable conditions contribute significantly to the overall agricultural production over the region. Over the time, conducive living conditions have resulted in a substantial rise in the population over the region. It accounts for close to one fourth (~24%) of the total population of the world (2019 estimate; source: World Bank, https://data.worldbank.org/). By population, this subregion stands top in Asia where more than 60% of the region’s total population is still rural and relies heavily on agriculture, natural resources and allied sectors for livelihood (Islam et al., 2009). The unique geographical settings and socio-economic-demographic structure of the region makes it highly vulnerable to the risks posed by climate change.

Figure 1. South Asian region.

Studies have documented the evidence of anthropogenic climate change post the industrial revolution era over the region. Through observations and dedicated studies done using the state-of-the-art climate models, human-induced climate change signatures alongside natural variations, have been noted in the form of increasing extremes (e.g. cyclones, droughts, floods, heat waves, thunderstorms etc), rising sea level and changing monsoon patterns over the region

(Hijioka et al., 2014; Vellore et al., 2016, 2020; Krishnan et al., 2020). Additionally, new developments as a result of population growth are putting further pressures on the urban environment, which contributes to the proliferation of slums, water scarcity and pollution of air, soil and water resources. This has brought adverse effects on ecological resources and is disturbing the socio-cultural ethos and general psychological wellbeing. It presents a greater challenge to society and the environment of the region. This highlights the need for improved understanding about physical processes and feedback among them to have better climate projections which can help in better planning and sustainable development over South Asia. It requires enhanced observations, modeling capabilities, and usage of advanced scientific techniques to extract more meaningful information from the data. The present chapter synthesizes the observed climate change and projections as available in the published literature, mainly (but not limited to) over the Indian region in South Asia. A brief discussion is also presented about the ongoing efforts and emerging methodologies to help better understand the science behind climate change and its attribution over the region.

2. Climate change over South Asia

Climate change manifests in various forms, including changes in frequency and magnitude of precipitation, temperature, extreme storms, sea level rise, warming trend etc. Using long term observational records and model projections of meteorological variables, several research studies have quantified these changes in mean state of the climate. Already visible impacts of climate change are seen over Asia in the form of gradually rising surface temperatures, increased variability in the precipitation and surge in extreme weather events (Hijioka et al., 2014). Figure 2 shows interannual variability through 1950 to 2019 in annual mean 2m air temperature and precipitation rate shown as anomalies (climatology used for the same period) averaged over the land area in South Asia (averaged between 5°N-40°N, 60°E-100°E; data obtained from NCEP/NCAR Reanalysis, Kistler et al., 2001). It can be seen that the interannual variability in surface temperatures have been considerably large during recent decades. Post 1970s there has been a significant rising trend in observed temperatures with pronounced warming since the late 1990s. Since the 1970s the annual mean temperature has risen by almost 1.5 °C while positive departures are seen every year since 1995. On the other hand, though annual mean precipitation rate showed less variability between the period 1960-1990, positive departures are noted in the decade of 1950s and during the recent years. Post 1990, the variability has increased and it has been more erratic since then. In recent years a slight rise is seen in the precipitation which has shot close to 0.4 mm/d.

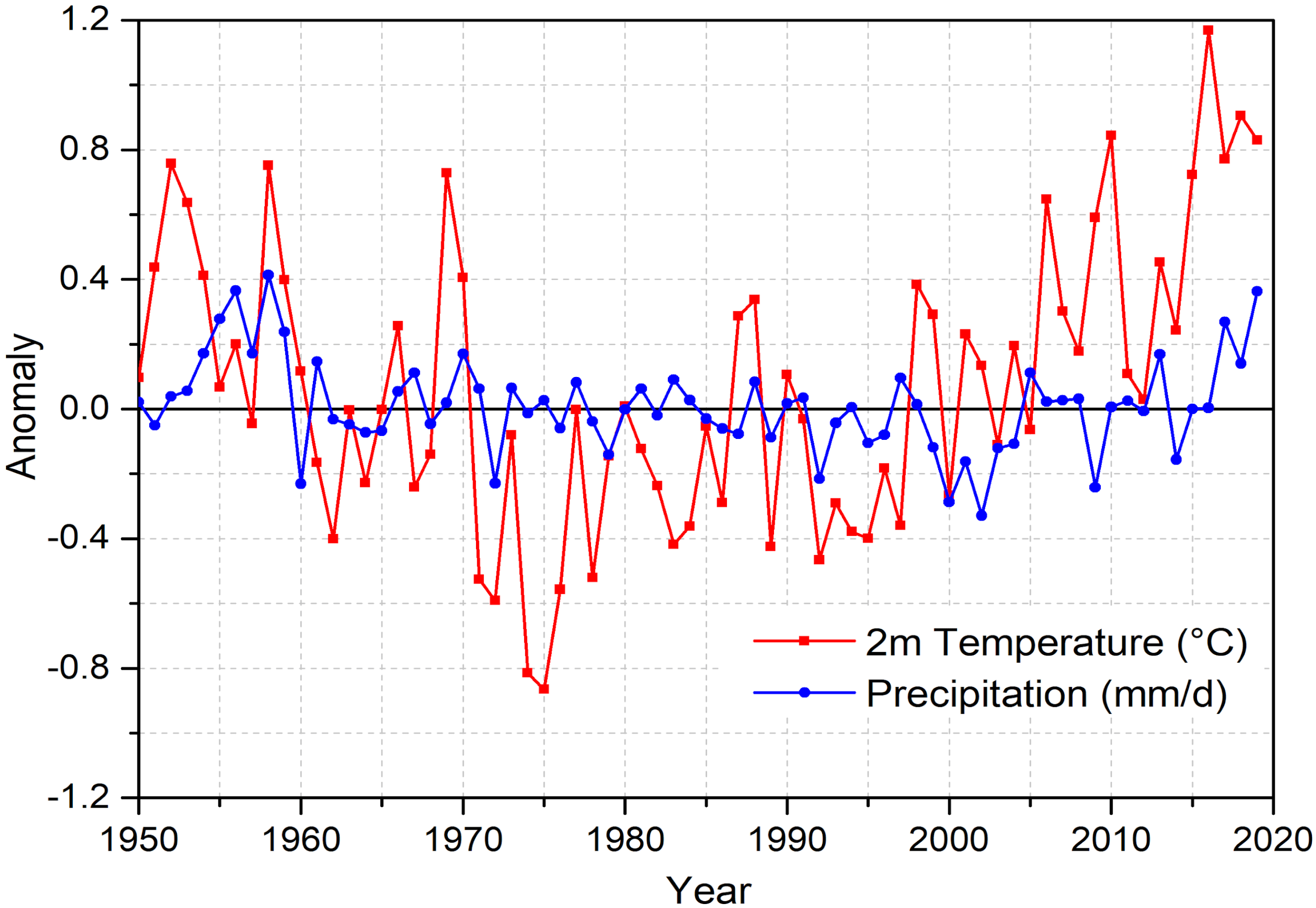

Figure 2. Interannual temperature and precipitation anomalies over land regions in South Asia averaged between 5°N-40°N, 60°E-100°E (climatology used for the full period 1950-2019).

Figure 2 clearly shows that temperature and precipitation over South Asia have shown large variations in the recent period when seen in the context of annual mean variability. However, significant changes in seasonal means have been documented by the previous studies. IPCC, through its series of exhaustive reports have documented the observed and projected changes in climate and its implications over different geographical regions of the world, including Asia. Recently a comprehensive climate change assessment report over India has been brought up by the Ministry of Earth Sciences (MoES), Government of India (Krishnan et al., 2020). Since the regional climate of South Asia is dominated by the changes over Indian region, henceforth the discussion would be mainly based on the climate change aspects as reported over India. The following sections summarize the findings from these reports and other published literature regarding the observed and projected climate change change over the region Particularly, a significant part of this chapter is based on the reports by Hijioka et al. (2014; and references therein) and Krishnan et al. (2020; and references therein).

2.1. Information from the past observations

Temperature and precipitation have significantly varied over most parts of Asia including significant changes over south Asia. The region has witnessed increasing annual mean temperature during the 20th century with 0.7 °C warming observed over India during the 1901-2018 period. This observed trend in recent decades has been largely attributed to anthropogenic activities. There has also been a decline in the number of cold days and nights and a rise in the number of warm days and nights. With rise in temperatures, frequency and severity of heat waves have also increased over the region. Precipitation has significantly varied and with considerable heterogeneity in patterns over different parts and seasons of south Asia. The seasonal mean rainfall over south Asia shows inter-decadal variability, with a noticeable declining trend and frequent occurrences of deficit monsoon years. Over India, there has been an increase in the number of monsoon break days and a decline in the number of monsoon depressions which have resulted in overall decrease in seasonal mean rainfall post 1950s. At the same time an increase in extreme rainfall events has been reported over the central India region. These changes have been linked to anthropogenic aerosols and regional LULC patterns over the region. With the changes in temperature and precipitation patterns since 1950, there has been an increase in drought frequency along with expansion in areas affected by drought. There has been a concurrent rise in flash flooding over different parts of the country due to rise in occurrences of localized extremes in rainfall. Observations show that the higher elevation regions of the Himalayas have warmed significantly at a rate of about 0.2 °C per decade. Though in recent decades, a significant decline in snowfall over Hindukush Himalayas was observed, parts of the Karakoram Himalayas experienced increased wintertime frozen precipitation assisted by Western Disturbances.

Indian Ocean has warmed significantly in recent decades with sea surface temperatures in the tropical Indian Ocean rising by 1 °C on average over the 1951–2015 period. The observed warming is linked to anthropogenic radiative forcing and long-term changes in monsoonal wind patterns. With the warming, thermal expansion of the water has led to sea-level rise over the region. The sea level changes in Indian Ocean are linked to changes in monsoon circulation, Hadley, and Walker cells. There has been a decline in annual tropical cyclone activity over the north Indian Ocean. However, observations indicate that frequency of very severe cyclonic storms have increased during the post-monsoon period in the recent decades.

2.2. Future projections

Based upon the results from the global and regional climate model simulations, various studies and reports have documented the increased susceptibility of south Asia to climate change consequences (Hijioka et al., 2014 and references therein; Krishnan et al., 2020 and references therein). Rise in annual mean temperature over India relative to the 1976–2005 period is projected to be in the range of 2.4–4.4 °C across greenhouse gas warming scenarios. With ongoing efforts to curb anthropogenic emissions and reducing carbon footprint over India, the aerosol emissions are anticipated to reduce. With such reductions in northern hemisphere aerosol emissions, monsoon is shown to be impacted more by the greenhouse warming effects in the later part of the 21st century. As the temperatures rise, the increased atmospheric moisture can lead to significant rise in the mean, extremes and interannual variability of seasonal monsoon precipitation. Rise is rainfall extremes projects increased flood occurrences in the future while increased interannual variability of seasonal rainfall can lead to increased occurrences of drought alongwith expansion in drought affected areas. With elevation dependent warming in force, warming over Himalayan region can cause faster glaciers and snow melt, enhancing the streamflow and compounding the flood risk over the river basins. The sea surface temperature over the tropical Indian Ocean is projected to continue the warming trend. However for the trade and monsoon wind regions, negligible changes or even a decline is projected in mean significant wave heights. With continued global warming and rise in Indian Ocean sea surface temperatures, very severe cyclonic storms are projected to increase over the region during the twenty-first century. Table 1 summarizes the discussions made in sections 2.1 and 2.2 and highlights the observed and projected changes in regional climate over the region.

Table 1. Observations and projections of climate change over South Asia (based on Hijioka et al., 2014; Krishnan et al., 2020)

Variable	**Observed changes**	**Projected changes**
Temperature	1. Annual mean near surface temperature has increased over south Asia, with 0.7 °C warming over India during 1901–2018. 2. Trends largely due to anthropogenic activities. 3. Decline (increase) in the number of cold (warm) days and nights. 4. Increase in heat wave frequency over large parts of Asia. 5. Significant warming over higher elevation regions of Himalayas at a rate of about 0.2 °C per decade. 6. With global warming, significant decline in snowfall over Hindukush Himalayas, while increased wintertime frozen precipitation over parts of the Karakoram Himalayas assisted by Western Disturbances.	1. Projected rise in annual mean near-surface air temperature by the 21st century is likely to be in the range of 2.4–4.4 °C relative to 1976–2005. 2. With anticipated cuts in the anthropogenic emissions, greenhouse warming is projected to dominate later. 3. Warming over high regions in the Himalayas can continue further.
Precipitation	1. Increase in the number of monsoon break days along with a decline in the number of monsoon depressions. 2. Overall decrease in seasonal mean rainfall post 1950s. 3. Increase in extreme rainfall events over the central India region. 4. Observed changes are likely linked to anthropogenic aerosols and regional LULC changes.	1. Projected increase in mean, extremes and interannual variability of seasonal monsoon precipitation. 2. Changes are projected to be dominated by greenhouse gas warming leading to increased atmospheric moisture content.

Droughts and Floods	1. Increase in drought frequency along with expansion in areas affected by drought since 1950. 2. Increase in flash flooding over different parts of the country. 3. Changes are coherent with the observed changes in temperature and precipitation patterns.	1. Projected increase in flood occurrences with the rise is rainfall extremes. 2. Enhancement in the streamflow by faster glaciers and snow melt over the Himalayas due to warming can compound the flood risk over the river basins. 3. Increased drought occurrences along with expansion in drought affected areas likely due to large interannual variability in seasonal monsoon rainfall.
Ocean SSTs and sea level	1. 1 °C increase in tropical Indian Ocean SSTs over the 1951–2015 period. 2. The observed warming likely linked to anthropogenic radiative forcing and long-term changes in monsoonal wind patterns. 3. Rise in sea level due to thermal expansion. 4. Changes in the sea level likely linked to changes in monsoon circulation, Hadley, and Walker cells.	1. SST over the tropical Indian Ocean is likely to increase further. 2. Negligible changes or even a decline in mean significant wave heights over the trade and monsoon winds region.
Tropical Cyclonic Storms	1. Decline in annual tropical cyclone activity over the north Indian Ocean. 2. Increase in the frequency of very severe cyclonic storms during the post-monsoon period in the recent decades.	1. Very severe cyclonic storms likely to increase over the twenty-first century. 2. The rise in frequency likely linked to global warming and increase in the Indian Ocean SSTs.

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3. Recent efforts towards understanding the regional climate change science

3.1. Advances in observational and modeling capabilities

Reliable understanding about regional climate change is more complex as it is not only influenced by natural variability and global climate change patterns, but it is also affected by local changes in land cover land use patterns, emission sources, air pollution in the backdrop of development and urbanization. Better understanding of science behind climate change over south Asia requires enhanced understanding about the physical processes acting and interacting with each other. This highlights the need for better observations and improvement in model physics for reliable projections at all scales in space and time. Many steps are being taken under the aegis of International and regional programs to have an increased observational network over the region consisting of measurements from direct, remote based and other platforms.

Along with increase in the observational network, the need for better regional climate change information has led to unprecedented efforts in climate modeling over the region. India has taken up the challenge and dedicated efforts on these lines have been made at the Centre for Climate Change Research at Indian Institute of Tropical Meteorology (CCCR-IITM), Pune. Major contributions have come in the form of generating an ensemble of high resolution dynamically downscaled future projections of regional climate over South Asia (Sanjay et al., 2019) and developing an Earth System Model to make better climate projections with emphasis on the regional monsoon (Swapna et al., 2015). The high-resolution downscaled projections of regional climate over South Asia have been developed as a part of the World Climate Research Programme (WCRP) regional activity Coordinated Regional Climate Downscaling Experiment (CORDEX; http://cordex.org/). Under the CORDEX activity, the high resolution downscaled projections of regional climate and monsoon over South Asia till the end of 21st century have been generated by the centre using a regional climate model (ICTP-RegCM4; Giorgi et al. 2012) at 50 km horizontal resolution. The datasets are deemed useful for impact assessment studies and for quantifying uncertainties in the regional projections. As the Earth System Models have emerged as a reliable tool to understand the interactions among atmosphere, ocean, land, cryosphere, and biosphere systems, these models are being increasingly used to understand the impacts of human induced perturbations on the climate system. CCCR-IITM made an important achievement by developing an Earth System Model to understand global and regional climate response to long-term climate variability and climate change. The first version (IITM-ESMv1) was developed by transforming state-of-the-art seasonal prediction model-the Climate Forecast System version 2 (CFSv2, Saha et al. 2014) into a climate model. The updated version IITM-ESMv2 has been developed recently, and it is the first climate model from South Asia to participate in the CMIP model intercomparison project and contribute to the IPCC AR6 assessment report. A brief overview of these dedicated modeling activities of the centre has been provided in the Interim Report on Climate Change over India (Krishnan, R., Sanjay, 2017). The Earth System Grid Federation Data Node at CCCR-IITM supports the CCCR-IITM climate model datasets (CORDEX-South Asia and CMIP6) and allows access to the climate data.

3.2. Advances in new technology and tools

With the availability of improved observations and model outputs, the need for better extraction of meaningful information has become a necessary requirement. In the last two decades, several advanced techniques have shown promising results. This section briefly presents some of these methodologies such as usage of complex networks, phase coherence analysis, causal theory, artificial intelligence and deep learning, and cloud computing enabled GIS techniques and their applicability in advancing the science of climate change over south Asia.

Complex Network is a graph consisting of non-trivial topological functionality which is often present in networks of real systems. This theory has recently been applied by Stolbova et al. (2014) to reveal that the Indian Summer Monsoon (ISM) network has three basic spatial domains: North Pakistan (NP), Eastern Ghats (EG), and Tibetan Plateau (TP). These structures are distinguished by high degree, high betweenness and the longest average lengths of geographic ties. The patterns observed in the NP, TP and EG regions are important for the synchronisation of extreme rainfall during the ISM. The study identified the central Gangetic plains and parts of Pakistan as the main sinks with high levels of moisture deposition during the south Asian monsoon season. Their findings suggest that ISM's timing and strength can be determined by tracking the evolution of dominant patterns by means of complex networks. Agarwal et al. (2018) proposed a new, complex network-based method using a statistical approach known as Z-P space to consider the qualitative and quantitative dimensions of group participants over a single rainfall station in the region. It reported that the high elevation, northern part of India was isolated from other areas while the southern peninsular area had good intra-community and inter-community ties. The study demonstrated that extreme-rainfall events in South-Central Asia, East Asia and Africa's monsoon systems are substantially associated. And there are succinct connexions between South-central Asia and the extratropics of Europe and North America. These studies clearly highlight that complex network approaches can help determine main node positions in climate networks that play a major role in influencing the community's climate. Similarly usage of recurrence analysis is now being used on time-series data to study variation or similarities which can help understand nonlinear dynamics and nonstationary processes, e.g. temperature and precipitation changes over the region. The usage of recurrence plots can reveal significant insights into the non-linear processes governing climate change over the South Asian region.

The current state-of-the-art Earth system data analysis is still dominated by correlation and regression approaches. Established causality approaches can provide deeper perspectives from hypothesis testing to causal assessment of physical models. However, a big challenge to broader acceptance of causal inference approaches is the absence of a credible benchmark database. Runge et al. (2019) address this void with causeme.net, which includes links to open software products. Sensibly applied causal inference methods promise to greatly advance the state-of-the-art understanding of complex dynamical systems. Di Capua et al. (2020) used causal discovery algorithms to assess the ISM circumglobal teleconnection hypothesis. They also implemented causal maps, a modern implementation of the Causal Influence Networks definition, and highlighted how this approach would solve correlation map limitations by eliminating false ties. The study showed that the technique can provide superior skills in 2-4-month lead-time seasonal monsoon forecasts, enabling better socio-economic planning for the region. Phase coherence, first observed by Christian Huygens in 1665, brings out the synchrony of periodic signals. The long term natural modes of climate variability are often periodic and therefore coherency among signals should be considered to better understand the physical science of the earth system. Using the phase coherence methodology, a recent study by Singh et al. (2020) reports that the strong volcanic eruptions facilitate improved synchronization of ENSO and ISM oscillations which enhances prospects for better seasonal monsoon predictions.

Alongside these advanced analysis techniques weather and climate sciences need to process vast and rapidly growing volumes of data to provide more reliable, less unpredictable and physically compatible inferences of the complex Earth system in the form of estimation, simulation and understanding. Machine learning in general and deep learning in particular provide promising resources to create new data-driven models for Earth system elements, building our understanding of Earth. Recent studies indicate that deep learning has potential applicability in advancing climate science at all spatial and temporal scales. For e.g. Dasgupta et al. (2020) have reconstructed the Madden Julian Oscillation index using machine learning for the pre-satellite era, which is an important component of coupled ocean-atmospheric variability and crucial for the weather patterns over South Asia. Therefore, recent progress in deep learning and allied technologies present a greater opportunity to work on different aspects of climate change science not only over south Asia but on global scale as well. With further advancements, data-driven machine learning approaches to geoscientific science will not substitute, rather supplement and enrich it highly. Reichstein et al. (2019) envisaged multiple synergies between physical and data-driven models, with the ultimate objective of hybrid modelling approaches for better understanding of the earth system science. Deep learning is now widely being used across various sectors and Table 2 lists the potential scientific issues and associated deep learning techniques that can be applied for better understanding and decision making over the south Asian region.

Table 2. Scientific issues and applicable deep learning approaches in climate science and allied sectors.

Scientific issue	**Applicable Deep Learning based techniques**
Extreme events, Land use land cover change, Nowcasting	Classification by convolutional neural networks (CNNs)
Downscaling	Generative Adversarial Networks, Convolutional neural networks
Modelling Fluid flows	Physics inspired convolutional neural networks
Seasonal forecasting	Convolutional Long Short term memory networks (ConvLSTMs)
Forecasting electricity demand and supply	LSTMs, CNNs
Modelling emissions from various sources, Modelling transportation systems demand	Various feedforward deep neural networks
Building energy forecasting	Deep belief networks, reinforcement learning and others
Smart Buildings	Deep neural networks (DNN)
Collecting Infrastructure data	Computer vision methods based on remote sensing data
Precision agriculture, monitoring peatlands, forests, ecosystems, biodiversity	Convolutional neural networks with unmanned aerial vehicles
River runoff prediction from unmeasured catchments	Regression based Convolutional neural networks
Predictions of atmospheric fluxes, Vegetation properties forecast	LSTMs, RNN, GRU, 1d CNNs
Climate finance and analytics	Deep learning based time series models

The advent of space-based remote sensing technology has revolutionised the ways of spatial data collection. Satellite data offers a synoptic and global overview of the land, water, and air. This promotes an interdisciplinary approach to studying the Earth as a whole. However, with the scientific and technological advancements, a surge has been observed in the data collection instruments/tools. It has increased volume and heteroge-neity of the data, and raised concerns for the proper handling and storage of data sets. For the monitoring and assessment of Earth's related processes and hazards, the fast retrieval of the data collected from these instruments is required. But, heterogeneity in data e.g., lack of integration and interoperability has limited our ability to interpret the processes. The issues of integration and interoperability amongst the datasets of the different origins are resolved with the advent of Geo-intelligence, which encourages the use and assimilation of intricate, multidisciplinary data for providing resolutions to earth science and social sciences based challenges. The emergence of open source cloud computing and GIS tools such as Google Earth Engine and QGIS have revolutionized the use of high-resolution satellite datasets for the applications in urban meteorology and building ready to use applications for societal benefits (Gorelick et al., 2017). At present, more and more data products such as reanalysis, ground based observations are being added to the Google Earth Engine to facilitate ready-to-use analysis of datasets which were previously out of reach of common researchers due to their large size or complexity.

Alongside the increasing observations and physics based earth system modeling approaches, the climate science community can utilize these emerging methodologies to better understand climate change science over south Asia.

4. Summary and future outlook

Observations and climate modeling studies have documented definite anthropogenic impact on climate change over south Asia. The region houses close to one fourth of the total population of the world where more than half of the region’s total population rely on agriculture, natural resources and allied sectors for livelihood. The unique geographical settings and socio-economic-demographic structure of the region makes it highly vulnerable to the risks posed by climate change. Therefore to have better clarity about the science of climate change, it requires improved understanding about the physical processes and feedback among the earth systems. Through the available literature, the chapter lists out past changes and future projections of climate over the region and briefly discusses the recent advancements in observational-modeling-analysis approaches for better conception of the involved processes.

It is also noteworthy that more and more people across South Asia are accepting climate change as an anthropogenic problem. This increased awareness about climate change impacts has led to the development of various national and state action plans and assessment reports on the subject. In recent times, there has been a surge in the focus on manpower development and expansion of observational networks across South Asia. There have been dedicated observational and modeling efforts led by India lately, to better understand past climate and generate better climate projections. Moreover, the emergence of new computing hardware such as GPUs and TPUs is expected to make the process of data-crunching increasingly easy and thus can offer greater insights for the science of climate change over the region. It is anticipated that by the next decade when industrial quantum computing becomes a reality, climate models can be the first to take advantage of the computational power and very high resolution forecasts and projections might become a reality. Already artificial intelligence based techniques are showing promise in improving the forecasts generated by the climate models. The age of cloud computing enabled HPC with advanced computer hardware and paradigm shifts in the computational world is poised to bring a revolution in the regional science of climate change over South Asia. With more and more reliable observations and advances in earth system modeling, these new technologies, statistical models, user perception-based models, and modern machine learning algorithms are now being widely used in advancing regional climate science information applicable in all allied sectors.

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