Preface

Milestones in Paleoclimate Studies in India: Future Perspectives

The Earth System has been continuously changing due to natural processes for the last hundreds of million years. In the recent past, since the industrial revolution, there is a rapid rise in temperature which is suggested to be related to large scale use of fossil fuels resulting in an increase in the abundance of greenhouse gases in the atmosphere. Hence, while assessing the future scenario and consequences of climate change, it is essential to understand the climate dynamics and causes (natural and anthropogenic) of climatic perturbations on various time scales. Our understanding of the future scenario of climate change and its effects depends upon how well we know the amplitude and patterns of past climate variability both in time and space. The instrumental records of climate variability are limited to a short duration, generally less than two hundred years, and thus do not cover all modes of climate change. Therefore, a longer time series of past records in conjunction with the instrumental records is essential to better understand the interactions between various components of the Earth system and the underlying mechanisms. The monsoon system exerts a strong influence upon the climatic conditions in South Asia and the associated monsoon rainfall has a great impact on the socio-economic and agriculture development in this densely populated region. Therefore, in the Indian context, past climatic reconstructions elucidate largely, the reconstructions of the past monsoon history.

The information related to past climatic changes can be retrieved from the study of climate-dependent natural processes. In recent years, several palaeoclimatological studies have been made using natural marine and terrestrial archives. However, the need of the hour is to bring together the results from both the marine and terrestrial studies to develop a holistic view of the climatic evolution spanning the last several millennia. This special section brings together research articles from renowned palaeoclimatologists and palaeoceanographers of India, covering a range of terrestrial and marine proxies used in palaeoclimate reconstructions. These articles provide an overview of the major research findings and highlight the current understanding of climate variability in India through time and new directions and future challenges for palaeoclimate research in the country. The thirteen contributions in this special section are based on different natural archives (fluvial sediments, lake deposits, marine sediments, ice cores, speleothems and tree rings) employing various palaeoclimate proxies such as sediment characteristics, pollens, elemental concentration, foraminifera, coccolithophores, the isotopic composition of carbonates and organic matter.

Tree-ring-width records of conifers in Himalayan regions are widely used to develop temperature reconstructions for different seasons on decadal to inter-decadal scales. Yadav and Singh (**page 189**) critically assess the available tree ring-based temperature records from the Himalayan region and report anomalies during certain time intervals, which they suggest to be related to the extreme events coinciding with the volcanic eruption and associated cooling. The authors suggest strong potentiality of tree ring records in deciphering short-term extreme events.

In the recent past, there have been several high resolution studies on palaeovegetation reconstruction in the Himalaya in response to past climate changes using palynological records for a longer time period. These studies have shown changes in monsoon variability pattern across the Himalayan region both in time and space. The western Himalaya is affected by both the Indian summer monsoon and western disturbances, whereas the eastern Himalaya receives precipitation only from the summer monsoon. Kar and Quamar (**page 195**) compare records of past changes in the vegetation patterns over the eastern and western sectors of Himalaya in response to the monsoon climate variations since the late Pleistocene. The authors observe that evidence of arid events of 8.3 ka and 4.2 ka and Younger Dryas (10.8–12.4 ka) was more prominent in the western Himalaya than in the eastern sector. The study is significant for better understanding the trends and future climate change impact.

Srivastava *et al.* (**page 219**) analyse the sedimentological record of a brackish water lake (Pangong Tso) situated in arid Trans-Himalayan region. Utilizing sclerochronological analysis approach combined with sedimentological data and luminescence ages, these authors inferred changes in the precipitation and temperature since 1.6 ka. Detailed geomorphic mapping along the periphery of the lake enabled them to identify palaeolake level strands. It was suggested that the late Holocene aridity was responsible for the rapid fall of the lake level.

Fluvial archives of river systems across different geomorphological-climatic zones of India are a valuable source of information about monsoon precipitation through time. Sinha *et al.* (**page 232**) present a review of the late Quaternary fluvial records in the north and northwest India in order to evaluate variation in fluvial response to the past changes in the monsoon climate. The authors record differential responses of river systems across the different climatic regimes and suggest that the climatic condition combined with geomorphic setting attribute to the region-specific river behaviour. The study provides better insight into the process-based understanding of river response to climate change.

Speleothems of the Indian caves have been studied by several workers for oxygen and carbon isotope measurements to record past rainfall. Many of these records span the last few millennia with some extending beyond. Band and Yadava (**page 244**) present an overview of palaeomonsoon reconstructions based on the Indian speleothems. They discuss the application, systematics of stable isotopes (oxygen and carbon) and trace elements in speleothems and current method of dating. They observed non-persistent periodicities in available oxygen isotope records due to the complex nature of the climate system.

The ice core records from polar regions provide critical insights into the understanding of the global climate system on high resolution time scales. Previous results of ice core studies clearly show that climate changes in past have been large and rapid, extending into tropical regions. Thamban *et al.* (**page 255**) in their studies on Antarctic ice cores, discuss the quasi-decadal and decadal to multidecadal modes of Antarctic climate variability in response to the solar forcing, Southern Annular Mode, ENSO and the Pacific Decadal Oscillation.

A shift in orbital parameter regulates the zonal average temperature over the mid-latitude region of northern Hemisphere and affects hydrological circulation significantly due to the variation in the potential temperature gradient. Using clumped isotope derived temperature records of terrestrial and marine archives spanning the last 50 kyr, Banerjee *et al.* (**page 265**) infer an evolutionary shift in the precipitation pattern over western North America, Mediterranean and southeast Asia since the Last Glacial Maximum. The study is important in the current scenario of global pCO_2 increase and warming, which is most likely to be responsible for a major change in mid-latitude climate and the Asian monsoon system.

The oxygen isotopic composition and trace element ratios of reef-building corals are widely used by palaeoclimatologists and palaeoceanographers for sea surface temperature estimation and to study past changes in ocean–atmospheric processes. Coral isotopic records are also found useful in palaeomonsoon reconstruction. Chakraborty (**page 273**) reviews the coral isotope records available from the Indo-Pacific region and demonstrates that coral records from a few specific regions are suitable for the reconstruction of Indian summer monsoon variability. He further suggests that corals from the Lakshadweep region and equatorial Pacific have strong potential in Indian palaeomonsoon study.

Denitrification in the Arabian Sea is a significant source of nitrous oxide – a potent greenhouse gas – to the atmosphere. Denitrification also reduces the oceanic inventory of nitrate and thus reduces CO_2 sequestration. Therefore, it is important to understand its evolution and the various mechanisms governing its variability. In this direction, Tripathi *et al.* (**page 282**) discuss denitrification variability on various timescales from millennial to million years using the nitrogen isotopes of the sedimentary organic matter. They report that during the last 10 million years, the denitrification first intensified during the Mid Pliocene Warm Period and the modern strength of denitrification in the Arabian Sea was established around 1 million years ago. In general, denitrification was weaker during glacial periods and stronger during interglacials. This study attains special significance in the current scenario of global warming when the oxygen-deficient regions where denitrification takes place are expected to expand.

Awasthi and Ray (**page 291**) present a review of multiproxy based palaeomonsoon records from marine and terrestrial sediment archives of the Indian subcontinent and surrounding seas. The sediment provenance proxy records are used to study past variations in monsoonal climate and its links with the weathering/erosion in the sources. The authors discover regional variations in the duration and intensities of various climatic events. They further suggest that the records of changes in sediment source and erosion in marine cores are influenced by additional factors such as sea-level change, migration of shorelines, river mouths and delta.

Coccolithophores are one of the major groups of marine carbonate producers in the pelagic environment, playing a vital role in the marine biogeochemical cycles. In recent years, this group has gained increased attention as a potential proxy for palaeoceanographic and palaeoclimatic reconstructions. Choudhari *et al.* (**page 307**) discuss biology, biogeography and preservation potential of the coccoliths and their applications in reconstructions of palaeotemperature, palaeoproductivity and palaeocirculation.

Various proxy-based palaeoclimate records, instrumental and historical records all show that the Indian monsoon varied at different time scales. From palaeoclimatic studies, it has been clearly established that the changes in the Indian summer monsoon were associated with the orbital parameter, solar insolation, shift in the position of the Intertropical Convergence Zone, El-Niño Southern Oscillation and changes in the Atlantic and Indian Oceans circulations. These inferences were broadly supported by a single model with uncertainties. As the climate models provide a way to understand future climate, it is essential to undertake a thorough evaluation of the performance of various climate models. Tejavath *et al.* (**page 316**) carried out a detailed analysis of outputs of five CMIP5/PMIP3 model simulations to identify past variations in the Indian summer monsoon intensity. However, the authors realize that there should be more efforts in the synthesis of data model and comparison of simulation outputs and proxy based palaeoclimate data assimilation in order to gain better accuracy of past climate reconstruction.

Study of the stable oxygen isotope composition of marine carbonate shells has significantly advanced our knowledge of the past climate variability on different time scales. In order to understand Indian monsoon variability, extensive work on oxygen isotope measurements of selected planktic foraminiferal species population has been carried out for the reconstruction of sea surface temperature. This bulk foraminiferal analysis approach provides averaged temperature signal, masking short-lived events like seasonal changes in sea surface salinity. The isotopic values of individual foraminiferal shell hold the ability to trace seasonal and short-lived events through the past. Thirumalai and Clemens (**page 328**) using this novel approach have reconstructed seasonal sea surface salinity gradients in the Arabian Sea in order to better understand the changes in monsoon seasonality.

This special section is dedicated to the memory of Prof. Rengaswamy Ramesh, who untimely passed away on 2 April 2018 at the age of 62 years. He had an illustrious career at Physical Research Laboratory, Ahmedabad for almost 40 years and later at NISER, Bhubaneshwar as Senior Professor in the School of Earth and Planetary Sciences. Ramesh was a true polymath and made an immense contribution, especially to the study of past climate variability of the Indian subcontinent using various isotopic and geochemical proxies from both marine and terrestrial archives. We hope that this special section having articles reviewing different proxies and their applications would be immensely useful for the palaeoclimate research community especially young researchers. We thank Dr M. Ravichandran, Director, NCPOR for the support and encouragement. We also thank the Chief Editor, Prof. S. K. Satheesh and the editorial staff for their kind help.

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