JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.68, September 2006, pp.347-352

The Indian Monsoon as a Component of the Climate System During the Holocene

R. R. KELKAR
ISRO Space Chair, Department of Atmospheric and Space Sciences, University of Pune, Pune 411 007, India
Email: kelkar_rr@yahoo.com

Abstract: The Indian summer monsoon is fundamentally a giant land-sea breeze produced by the heating of the Eurasian land mass and the relative cooling of the Indian Ocean. It is a significant component of the climate system as it has global linkages through El Niño-Southern Oscillation (ENSO) and other factors. Changes in the land-ocean temperature contrast can have a profound influence on the strength of the monsoon winds and precipitation. Although India is fortunate to have instrumental records of rainfall dating back to the 18th century, it is important to investigate how on geological time scales, the monsoon may have responded to variations in the incoming solar energy, the earth's orbital characteristics and glacial boundary conditions.

For reconstructing past monsoon episodes, recourse has to be taken to proxy data as indirect evidence of what the conditions might have been like. There are many high-resolution proxy indicators such as width and density of tree rings in the Himalayan forests, geochemical characteristics of Arabian Sea corals, laminated ocean-floor sediment cores off the west coast of India, lake-bed pollen sequences from northwestern India, and high-elevation ice cores from the Tibetan region. It must be realised that inferences drawn from proxy studies are bound to have limitations and uncertainties and cannot be expected to match the accuracy of analyses carried out with recent meteorological data. However, for studies on time scales of hundreds to thousands of years, there is perhaps no alternative to the use of proxy data.

It is now generally agreed that the climate of the Holocene was relatively stable, but was characterised by millennial scale variability and long-term trends including changes in the nature of ENSO. As more results emerge from proxy studies, we would be in a better position to re-construct past monsoons, droughts and floods over the Indian region. If parallels to the present global warming trend were discovered in the historical past, they would help in building better monsoon prediction models.

Keywords: Monsoon, Climate system, Holocene, Rainfall variability, Trends, Global warming.

INTRODUCTION

In recent years, the global climate has been exhibiting signs of change that can neither be overlooked nor fully explained in terms of natural climate variations (Burroughs, 2003). In this context, scientists, environmentalists, policy makers and others interested in the subject of climate change have been posing several fundamental questions like:

- Is the earth's climate really changing?
- How has the climate changed in the past?
- Why does climate change?
- How much is the human influence on climate?
- What will the future climate be like?
- What are the likely impacts of climate change?

These questions are not new, but we are in a much better position to answer them today than ever before. We have come a long way towards a clearer understanding about connections among the different components of the climate system, the nature of the feedback mechanisms and the natural dynamics of the earth system. We have quantitative details and process-level understanding, and uncertainties have either been reduced or accepted.

The climate system is subjected to external forcings like the incoming solar radiation, and is also influenced by internal interactions among its five components viz., the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. In the past, scientists have treated them individually and it is only now that the linkages among these components are being brought into proper perspective. For example, the radiation budget of the earth-atmosphere system was regarded almost completely as a balance of purely physical processes. Now, human influence on the

0016-7622/2006-68-3-347/$ 1.00 © GEOL. SOC. INDIA

atmospheric composition, particularly through the addition of greenhouse gases and aerosols, is being duly considered. Our definition of climate as an invariant mean has itself undergone an alteration, with climate variability and extreme events being given as much importance as the mean state. That climate change could be natural as well as induced, has given rise to a whole new science of climate prediction.

Methods of Reconstructing Past Climates

To determine whether the 20th century warming is unusual, it is essential to place it in the context of past climate change. There is a growing concern about the increasing impact that human activities are making on the environment. Climate change resulting from anthropogenic activities will be superimposed upon the natural climatic variability. A key to the prediction of future climate change, therefore, lies in understanding the causes and characteristics of its variability in the past.

Instrumental records are available only for the last two centuries or so at best. Estimates of global climate variability during the past can, therefore, be drawn as indirect inferences from the so-called "proxy" indicators. A proxy indicator is a local record that can be interpreted using physical or biophysical principles to obtain past climate-related information. It is necessary here to filter noise or false signals not related to climate. It is also desirable to match two or more independent proxy indicators for corroborating the results. Examples of proxy indicators are tree rings, corals, lake- and ocean-bottom sediments and bore-hole measurements.

At middle and higher latitudes or where there is seasonality in temperature and precipitation, many species of trees develop annual growth rings. Tree rings are indirect indicators of the environmental influences upon their growth during their lifetime. This new science of "dendrochronology" is essentially a process of assigning of individual years to each ring (dating), through a detailed study of ring characteristics like width and density, matching between trees (cross-dating) and combining data from a number of trees in a region to establish a tree ring chronology. Tree ring research has yielded indirect information about environmental change over the past hundreds of years and helped long-term reconstruction of palaeoclimate.

Corals found in the shallow waters of tropical and sub-tropical oceans are another source of information that can complement tree ring data from land. Corals have a similar structure, with a new ring added each year. The ring structure can be analysed by drilling into the coral's core. Corals can provide vital indications of past climate in El Niño-Southern Oscillation (ENSO)-sensitive regions of the world.

Yet another significant data source is ice cores extracted from the polar regions of Canada, Greenland and Antarctica and other alpine and subtropical regions. Ice core analysis includes measurements of oxygen isotopes, concentration of salts and accumulation of precipitation, both annual and seasonal.

Most significant results have emerged from the analysis of the 420,000-year records of the ice cores recovered at Vostok in Antarctica in 1999 (Fig. 1). The temporal dynamics of global temperature and of the global carbon cycle, as represented by the atmospheric concentration of trace gases (CO_2 and CH_4), are tightly coupled and show very similar patterns throughout the period of the record. There are four cycles of 100,000-year periodicity. The values fall recurrently within the same envelope through the four cycles over the last half a million years.

This systemic behaviour of the earth's environment is due to a combination of external forcing, primarily variations in solar radiation levels at the earth's surface, internal forcings within the earth's environment itself and a large and complex array of feedbacks. An important outcome of the ice core data analysis is the realization that it is the *internal* dynamics of the system, rather than *external* forcings, which undoubtedly maintain our planet in a condition that is habitable for life.

Other proxy data are those derived from lake- and ocean-floor sediments, at latitudes poleward of the tree-line, annually laminated lake-bed sediments, and such other high-resolution data including bore-hole measurements.

Northern Hemispheric Temperature Reconstructed over the Last 1000 Years

Figure 2 shows the variation of the Northern Hemispheric temperature average relative to the 1961-1990 AD average. The purple line is a 40-year average whereas the grey band is an indicator of the uncertainty. It is evident that the past decade may have been the warmest of the millennium. The period covering the 11th-14th centuries AD was relatively warm, whereas the time spanning the 15th-19th centuries AD was relatively cool. There are definite indications of the existence of the so-called "Little Ice Age" as well as the "Medieval Warm Period" although there the data suggest that these might have had some regional variations and were not necessarily coincident or synchronous globally.

What emerges is that the climate of the Holocene period is characterised as the longest stable warm period in the past 400,000 years. It is marked by millennial scale variability and the Early Holocene may have been warmer than the 20th century AD. The timing of the occurrence of

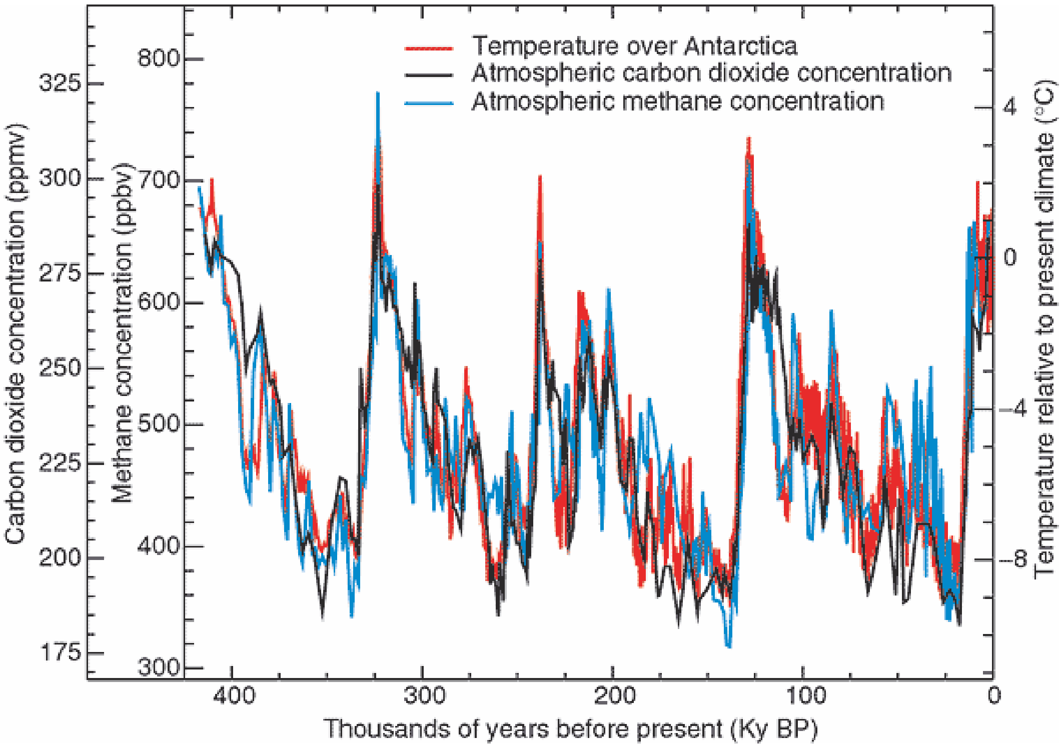

Fig. 1. Variations of temperature, and methane and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctica (Source: IPCC Web Site www.ipcc.ch).

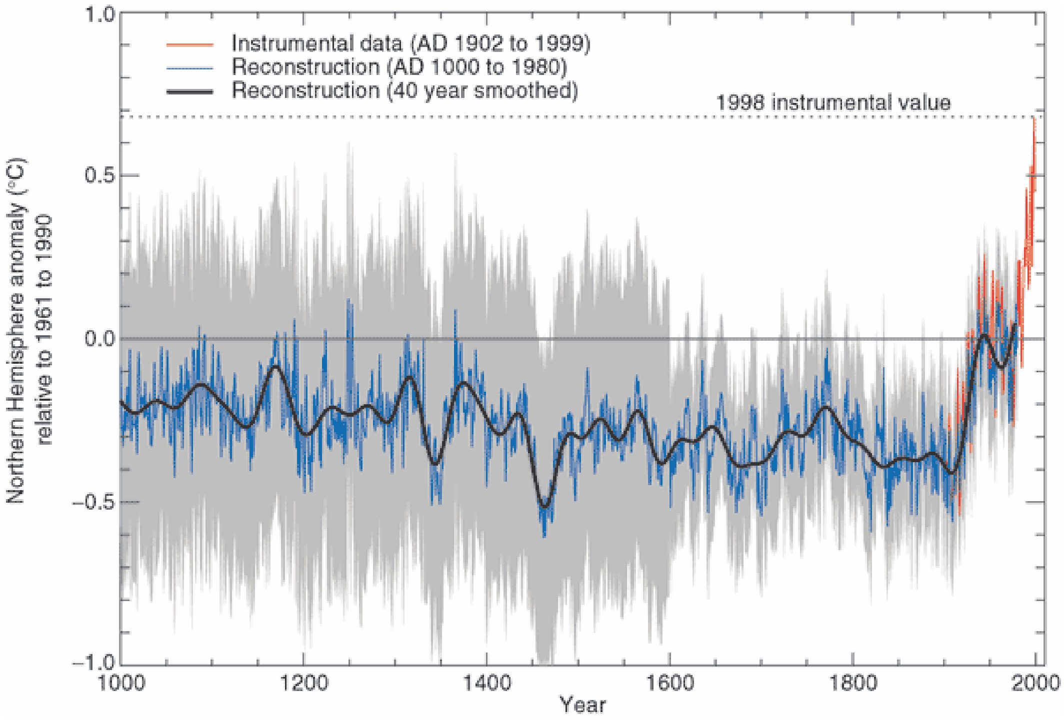

Fig. 2. Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from 1000 to 1999 AD, smoother version of NH series (black), linear trend from 1000 to 1850 AD (purple-dashed) and two standard error limits (grey shaded) (Source: IPCC Web Site www.ipcc.ch).

maximum warmth is different across the globe and long-term trends are seen in the nature of the ENSO phenomenon.

The Indian Monsoon as a Component of the Climate System

From palaeoclimatic studies of the Indian Monsoon, it is postulated that four monsoon maxima occurred during the last 150,000 years in association with solar radiation changes because of orbital variations and glacial boundary conditions. Model results are consistent with palaeo-evidence (Rupa Kumar et al. 2002).

Pollen density sequences from lake-beds of northwestern India and lake levels suggest that the monsoons were weak before 18,000 years B.P., that a warm and humid climate existed between 10,000 and 5,000 years B.P. or early Holocene, and that a trend towards aridity set in around 3,500 years B.P. Tibetan ice core analyses indicate prolonged drought during the 18th century AD. Extensive sampling of tree rings over western Himalayas has shown signatures both of the Little Ice Age and the Medieval Warm Period. The northern limit of the monsoon reaching the desert margins has undergone wide fluctuations in the past, coinciding with the rise and decline of civilizations such as the Indus Valley Civilization (2300-1700 BC), ‘Painted Grayware’ Culture (700-300 BC) and the Rangamahal Culture (100-200 AD).

The Indian monsoon finds a mention in many scriptural, mythological, historical and literary writings. Kautilya (ca. 300 BC) discussed the importance of rainfall measurement in his *Artha-śāstra*. Kalidasa (ca. 400 AD) traced the path of monsoon clouds in his romantic epic *Meghadoota*. *Varāha-mihira* (ca. 550 AD) attributed rain to the Sun in his *Bṛhat-samhita* as *“Adityat Jayate Vrishtih”* which is incorporated in the logo of the India Meteorological Department.

It was in 1686 AD that the British astronomer-scientist, Edmund Halley, explained to the Royal Society of London the genesis of the Indian summer monsoon as a giant land-sea breeze phenomenon resulting from the differential heating of the Indian Ocean and the Eurasian landmass. Halley predicted, in 1705, using Newton’s laws that a comet seen in 1682 would return in 1758. The comet did return as predicted and was later named in his honour.

India is fortunate to have some of the longest records of meteorological observations. The British East India Company set up rain gauges in 1785 AD at Calcutta (now Kolkata), in 1792 AD at Madras (now Chennai), in 1823 AD at Bombay (now Mumbai) and in 1840 AD at Simla. By 1850 AD, there were 50 rain gauges across the country. The India Meteorological Department was established in 1875.

If one looks at the Indian southwest monsoon seasonal rainfall for the country as a whole over the past 129 years (Fig. 3), it is apparent that there is no increasing or decreasing long-term trend. However, the Indian monsoon does have a strong inter-annual and decadal-scale natural variability. Even the drought of 2002 is at the lower end of the documented natural variability and is not an unprecedented catastrophe. The year 2002 AD has confirmed that the Indian monsoon never fails totally.

The Scientific Basis of Weather Prediction

Often, it is not realized that weather is governed not only by dynamical and physical processes within the atmosphere, but also by the interactions of the atmosphere with land, ocean and ice. Assuming that all these processes can be modelled, and the state of the atmosphere, ocean and land is known at any given time, a future state of the atmosphere can, in a conceptual sense, be scientifically predicted. But in reality, such a possibility is severely restricted because of many reasons: atmospheric processes are essentially non-linear, our understanding of all the processes is not complete, all required inputs may not be available or cannot be observed, and there is a wide spectrum of time and space scales of atmospheric motion.

As of now, it must be accepted that because of the chaotic nature of atmospheric processes, weather forecasts cannot be made beyond two weeks. But paradoxically, a prediction on climate scale is scientifically possible and is likely to succeed to a limited extent. This is because oceans have a large thermal inertia and land surface characteristics persist over a long time. So, the variability of the surface boundary layer extends over many seasons, i.e. much longer than the predictability of the atmosphere alone. Climate prediction is an attempt to produce a most likely description of the evolution of the climate on seasonal, inter-annual and longer time scales.

Techniques of Long-Range Monsoon Prediction

Statistical models use linkages between the monsoon rainfall and antecedent global land, oceanic and atmospheric parameters. Dynamical models solve complex mathematical equations governing atmospheric and oceanic processes, using initial data and surface boundary conditions and integrating them over time. In statistical models, a parameter cannot be chosen on the basis of high correlation alone. It must also be physically explainable. Only gross features of the monsoon rainfall can be predicted because correlations become weaker as we go to shorter time scales and smaller space scales (Rajeevan et al. 2004).

If the model has too many parameters, some of them

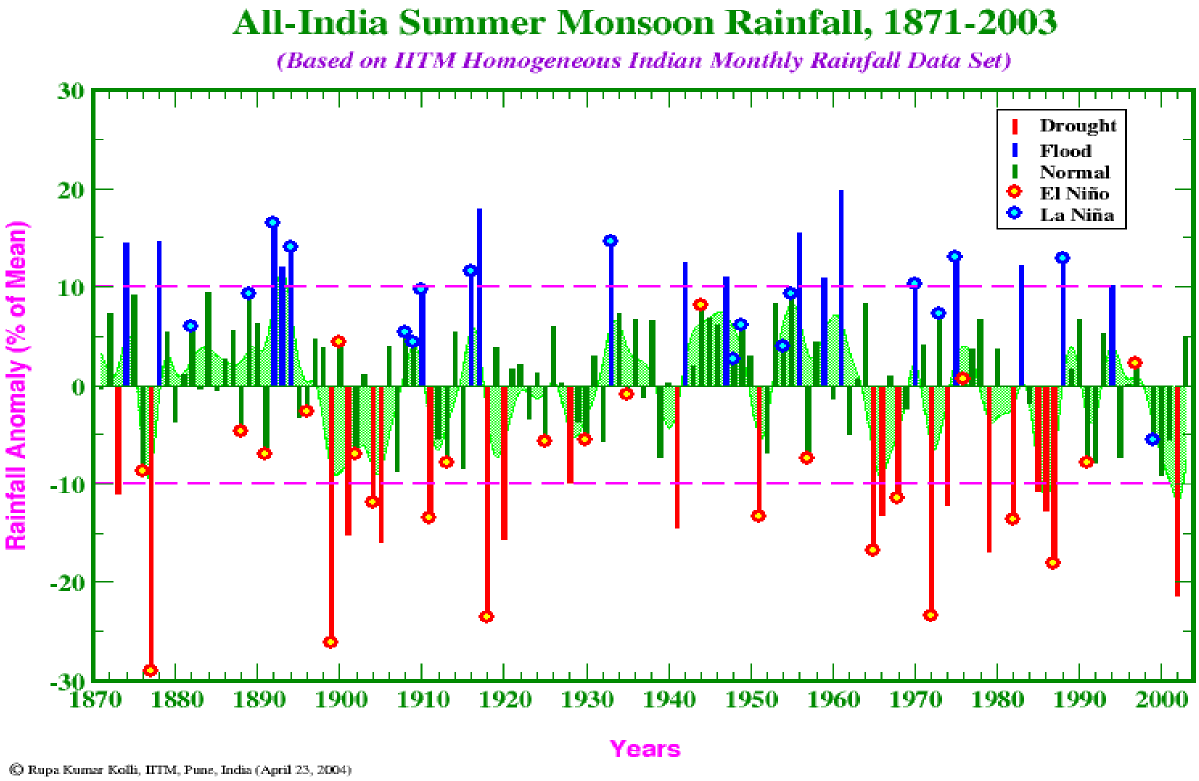

Fig. 3. Time series evolution of All-India Southwest Monsoon Rainfall anomaly, expressed as percent departure from its long-term mean, over more than a century in the past. (Source: IITM Web Site www.tropmet.res.in).

could be inter-related. Correlations change with time and slowly lose their significance. No statistical correlation can be 100 %. Therefore, statistical models will always have some element of uncertainty (or model "ignorance") and could occasionally go wrong.

Dynamical or numerical models have problems dealing with tropical convection. Model simulations are known to be sensitive to resolution and physical parameterizations of the model and are also very sensitive to small changes in the initial conditions. This is a problem for us as India is surrounded by data-sparse areas like oceans, mountains and deserts. However, with numerical models, detailed predictions are possible. Before an atmospheric model can be used to predict monsoon *anomalies*, we must be sure that it can simulate realistically the *mean monsoon circulation.* We must also know how accurately the model can convert the circulation features into *rainfall amounts*. Dynamical models have not yet reached the desired level of perfection.

Projections of Future Climate Change and their Likely Impact on the Monsoon

It must be remembered that the results of any climate model could have uncertainties due to non-availability of data required by the model (both in terms of quality and quantity), as well as an incomplete understanding of atmospheric, oceanic, physical, chemical, geological and other processes that drive the climate system. An inadequate parameterisation of these processes in the model, which may also perhaps be due to computational limitations, will affect the accuracy of the predictions. Models also use many "scenarios" of the future state of the world, and these may actually turn out to be different. We, therefore, have to contend with only "projections" of the future climate change and not "predictions".

Human influences are expected to change the atmospheric composition throughout the 21st century. Projections of future climate change are derived from various emission scenarios of greenhouse gases and aerosols. The Intergovernmental Panel on Climate Change (IPCC, 2002), in its Third Assessment Report, has come up with 40 future scenarios falling into four "storylines", but global warming and sea level rise are common features of all the scenarios, with the surface temperature rise being in the range of 1.4 - 5.8 °C between 2000 and 2100 AD.

A feature of global warming which is not often given due emphasis is that the rate of warming is relatively higher over the Northern Hemisphere (land) than the southern hemisphere (ocean). This implies a stronger land-sea thermal gradient, which drives the Indian monsoon. Increased land-sea temperature contrast should be conducive to stronger monsoons. This is beneficial but, in turn, implies a higher frequency of flood events. Further, as there is a strong correlation between mean precipitation and its inter-annual variability, both floods and droughts are likely to be affected.

The sea level rise resulting from climate change is likely to have many impacts on our 7500 km long coastline. We also have many big and small islands. Coastal zone management becomes very important in the context of climate change, and should involve regulation of land-use, proper planning of developmental activities, eg. new ports, industries etc., measures for protection from increased flooding and against coastal erosion, and conservation of natural ecosystems (Noronha et al. 2003).

CONCLUDING REMARKS

Until recently, human activities have been considered to be an insignificant force in natural dynamics. Today, their impact has begun to match, and even exceed, that of natural processes. Fossil fuel reserves that were generated over a period of several hundred million years are now on the verge of depletion. As much as 50 % of the land surface has been transformed by direct human action, with significant consequences for biodiversity, nutrient cycling, soil structure, biology and climate. More nitrogen is being fixed synthetically and applied as fertilizers in agriculture than what is fixed naturally in all terrestrial ecosystems.

More than half of all accessible freshwater is used directly or indirectly by humankind, and underground water resources are getting depleted rapidly in many areas. Concentrations of several climatically important greenhouse gases, in addition to CO_2 and CH_4, in the atmosphere have substantially increased. Coastal and marine habitats are being dramatically altered. The magnitude, spatial scale and pace of human-induced change are all unprecedented. The time scale of these changes is of the order of decades to centuries, and not of the order of millennia as in the past.

It appears that we are in a process of transition from the Holocene into a new epoch, for which the Nobel Prize winner, Paul Crutzen, and other scientists have coined the term “Anthropocene”. We would still be in the Quaternary Period of the Cenozoic Era in the Phanerozoic Eon. The name emphasizes the emerging and central role of humankind as a geological and ecological agent.

References

Burroughs, W. (2003) Climate into the 21st Century. WMO, Cambridge University Press, 240p.

IPCC (2002) Climate Change 2001: Synthesis Report. Cambridge University Press, 1000p.

Noronha, L., Choudri, B.S. and Nair, K.S. (2003) Environmental Threats, Vulnerability and Adaptation. TERI, Mumbai, pp.121-142

Rajeevan, M., Pai, D.S., Dikshit, S.K. and Kelkar, R.R. (2004) IMD’s new operational models for long-range forecast of southwest monsoon rainfall over India and their verification for 2003. Curr. Sci., v.86, pp.422-431.

Rupa Kumar, K., Krishna Kumar, K., Ashrit, R. G., Patwardhwan, S.K. and Pant, G.B. (2002) Climate Change and India. Tata McGraw Hill, New Delhi, pp.24-75.