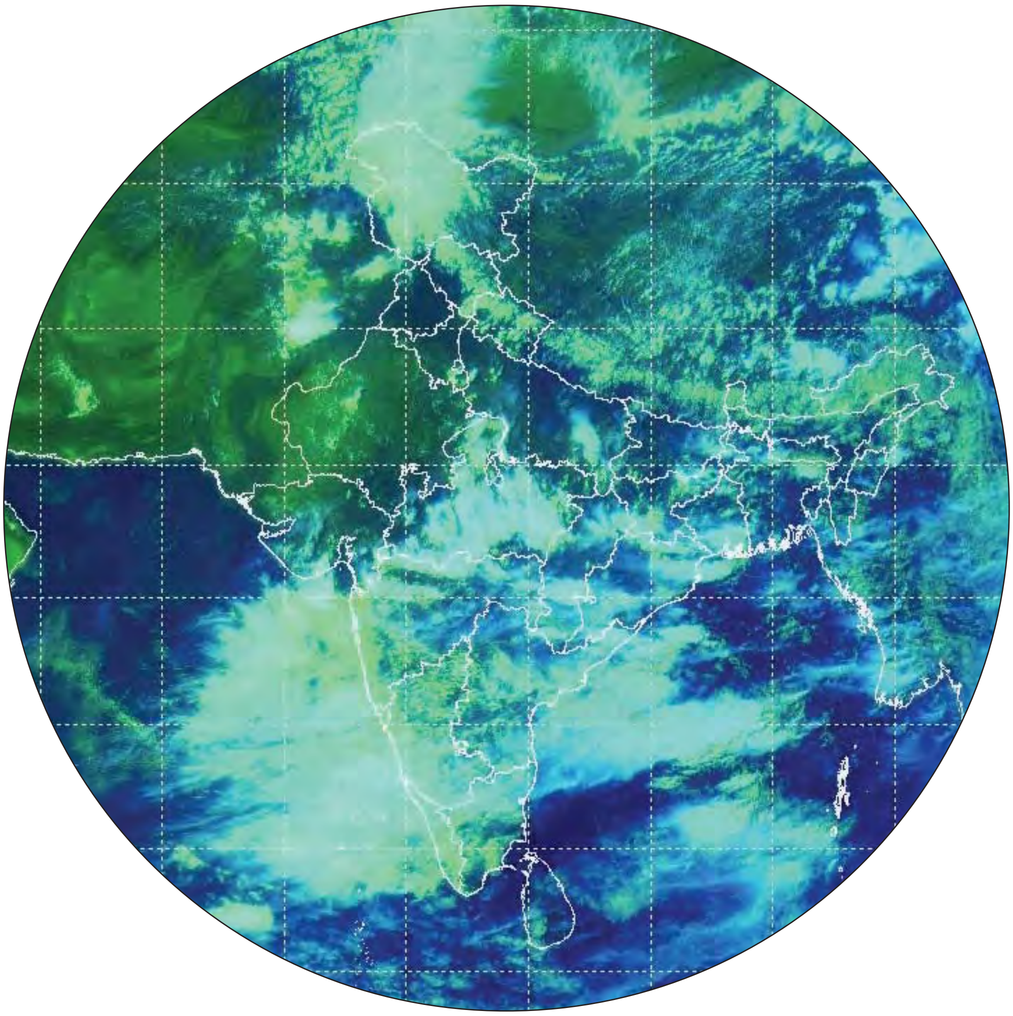
IGBP-WCRP-SCOPE-Report Series: 4

PALEOCLIMATE STUDIES IN INDIA

Last Ice Age to the Present



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Paleoclimate Studies in India: Last Ice Age to the Present

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Foreword

The Indian National Science Academy (INSA), New Delhi, is the adhering body in India to the International Council for Science (ICSU) and its affiliated International Unions / Committees / Commissions. A joint National Committee of IGBP-WCRP-SCOPE formed by INSA nurtures the activities of various projects in these programs. The Committee decided that a series of status reports be prepared on specific topics of these programs by leading Indian experts to highlight the Indian work at various fora and contribute to general awareness about Global Change among scientists and science students, policy makers and the public in general.

Recent assessments of the state of the environment across India indicate that the country's rising economic prosperity is also putting the environment under enormous stress. The questions that now confront us are, whether, we understand the full magnitude and impact of this change. In the Indian context, climate change is largely the changes in monsoon. We do know the intensity of monsoon has varied over various spatial and temporal scales. We also know that the monsoon has never failed (that is there has never been a case where there was no monsoon rainfall) and that it will perhaps never fail being a stable atmospheric system. The droughts, famine and floods are a result of variability of this system around a mean annual rainfall of ~80cm. What we do not know and need to know in greater detail is that how this system will vary with anticipated changes in environmental parameters, for example, in global temperatures. We have limited knowledge on how the change will be spatially distributed and how will it be processed by the Earth System as the change progresses. Given that India depends almost in totality on monsoon rainfall for agriculture, understanding of this system and its responses to global temperatures and related changes becomes crucial to our food and water security and hence the economic prosperity. Sustainability of agriculture will be critically dependent on how well we can quantify and prepare for changes in monsoon.

The present booklet deals with the current understanding of climate of India through time. It outlines the key issues in climate change studies in India, discusses the methodologies and then presents a summary of what we understand in respect of climate/monsoon change. The book also outlines the future challenges for research in this area with the aim to stimulate further discussion and research in the country. The synthesis hopefully will form a key input to the research initiatives of International Geosphere –Biosphere Program and the World Climate Research Program through their PAGES and CLIVAR activities.

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Preface

Climate change is known to occur for the past several hundreds of million years. Geological records of these changes are seen in various continental and marine settings. Several important questions arise on various aspects of climate change. These questions pertain to the intensity of climate change and its possible impacts under the recent scenarios of the impact of Mankind on Earth System Components. Newer Questions such as, whether we have crossed the tipping points of the climate system and whether we have adequate time to respond to the effects of climate change are beginning to emerge. These questions are best answered by an informed understanding of the style of natural variability of Climate. Paleorecords enable the estimation of the amplitude and time scales natural variability of the climate system and help understand as to how the Earth System components processed such changes during the past.

At the request of the IGBP-WCRP-SCOPE National Committee, Professors. AK Singhvi, Physical Research Laboratory and VS Kale of the University of Pune have distilled the current state of paleoclimate research in India based on various climatic archives and the state of the research in the country. These authors summarize the current knowledge as well as identify areas for future research for informed decisions on further research and policy.

The article provides state-of-the-art review integrating India-specific information and global literature as appropriate. I consider that the material provided here will be of use to scientists, science students, policy makers and the public interested in global change issues of IGBP-WCRP and SCOPE.

JS Singh

JS SINGH
Chairman (2005-2008)
IGBP-WCRP-SCOPE National Committee

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1. INTRODUCTION

Since the dawn of civilization, climate has been a matter of great economic and societal importance. The growth and demise of numerous civilizations, domestication of plants and animals, beginning of agriculture, migration of people and societies, growth of urban settlements have all been directly or indirectly related to changes in climatic conditions. The quest to understand climate change has become more intense in recent times largely on account of anticipated global warming scenarios, which may affect the climate patterns and hence, the food production and life styles of people. Several basic questions arise in this context, e.g.

1. Can such climate changes be anticipated and can their magnitudes be predicted?
2. Can the response of the Earth system to perturbations in its environmental parameters be quantified?
3. Can this information be used for future planning of water resources and food security under changing climatic conditions with extreme climatic excursions embedded in it?

To address these questions a recourse is taken to reconstruct the past climates of various regions and use the information on the past changes to provide the necessary baseline data of climate variability (sans human interference) that can serve as analogs for the future. Such a data base when compared with the present data can help quantify and characterize the implications of such a change.

Modern records of climate change from instrumental data (thermometers, rain gauges) cover only a short span of time, less than two centuries. Due to their limited time coverage, the "instrumental" or "systematic" records do not capture all modes of climate variability. Therefore, recourse is taken to reconstruct longer time series of past records that can be used conjunctively with the modern instrumental records to better understand climate variability and *ipso facto* better understand the Earth, as a system comprising interactions and feed backs among its reservoirs viz. the geosphere, biosphere, atmosphere and hydrosphere, with added elements of human induced perturbation in each of these reservoirs.

Paleoclimate – Definition

Climate is a long-term average of weather conditions. Climatology, prior to the instrumental records of temperature, precipitation and other weather elements is referred to as "*paleoclimate (*also *palaeoclimate)*" or past or ancient (Greek *Palaios* meaning ancient) climate. The science of past or ancient climates is known as "*paleoclimatology* (also *palaeoclimatology*)". It is different in many respects from the study of contemporary climates (climatology) which deals with the investigations of present-day climate mainly on the basis of instrumental records and modeling.

Recent reconstructions of past climates have revealed that large changes in temperature and rainfall have occurred over almost all time scales ranging from decades to centuries to millennia and spatial scales from small regions to almost the entire globe. Some of these past changes were widespread and massive compared to those available in historical records of climate.

Causes of Climate Change

Climate refers to the average, or typical, weather conditions (mainly temperature and precipitation) observed over a long period of time (usually over 30 years) for a given place, area or region. Climate change refers to a significant shift from the longer term average weather conditions at a place or a region. There are two main causes of climate change:

1. Natural, and
2. Anthropogenic

Natural Causes

The natural causes of climate forcing include changes in the Earth's orbital parameters (related to the Sun-Earth geometry), variations in the Sun's output and volcanic eruptions. Volcanic eruptions inject dusty material into the atmosphere that decreases the net solar radiation reaching the Earth's surface. These in turn cause changes in the energy balance and hence alter the atmospheric circulation patterns. Volcanic eruptions, however, are short lived phenomena and hence are responsible for short-term (few years) changes in the climatic conditions. Periodic variations in the amount of energy emitted by the Sun, as indicated by sunspots, have been linked to climatic changes on the Earth. It has been known for a long time that the number of sunspots varies on timescales of 11 years, 80 years and longer. The Little Ice Age during the 17^{th} and 18^{th} century and the warming of the 20^{th} century has been attributed to changes in the solar output.

The long-term episodic occurrences of colder periods (Ice Ages or glacial periods) and warmer periods (interglacial periods) during the last couple of million years have been associated with changes in the Earth's orbital parameters. A Serbian mathematician Milutin Milankovitch first identified the cyclic changes in the Earth's orbital parameters, eccentricity, axial tilt and precession. These three cycles are collectively known as the Milankovitch Cycles.

Eccentricity refers to the shape of the Earth's orbital path around the Sun. The shape changes between, more and less, elliptical and circular at an interval of approximately 100,000 years. The axial tilt refers to the inclination of the Earth's axis in relation to its plane of orbit around the Sun. Changes in the degree of Earth's axial tilt (between 21.5° and 24.5°) occurs on a periodicity of 41,000 years. Precession is the Earth's slow wobble as it spins on its axis. This wobbling has a periodicity of 23,000 years and these changes cause changes in the Earth climate with similar periodicity.

Anthropogenic Causes

Large-scale use of fossil fuels, massive deforestation and major changes in the land use and land cover have contributed to an unnatural and alarming rise in the greenhouse gases in the atmosphere since the Industrial Revolution. The greenhouse gases absorb the outgoing terrestrial thermal energy and cause more warming than what should occur naturally. Based on detailed measurements, it is now suggested that the anthropogenically enhanced greenhouse effect would lead to a major shift in global climate (IPCC AR 4). Figure 1 provides observed changes in some of the key climate indicators viz. global average temperature, average sea level and northern hemisphere snow cover with respect to the values in 1961-90 (taken from IPCC AR4 report).

A recent analysis of sea surface temperatures of Arabian Sea suggests that it is experiencing a regional climatic shift since 1995 which has resulted in several fold increase in the occurrence of most intense cyclones, progressively warmer winters, decrease in monsoon rainfall and 16-fold reduction of wheat production. This is attributed to CO_2 driven warming that seems to upset the overall thermal structure of the Arabian Sea and suggest the impact of anthropogenic activities that are likely to affect the future food security in an indirect but substantive manner (Prasanna Kumar *et al*., 2005).

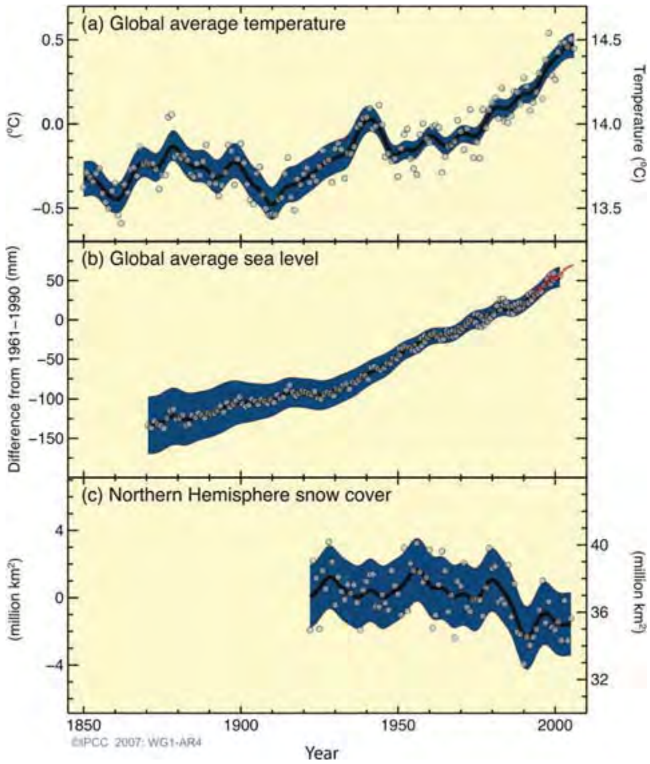

Fig. 1: Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). Reproduced with permission from IPCC AR4.

The Quaternary Period

The 'Quaternary Period' is the fourth and the latest geological period that commenced about 2.6 million years ago (previously placed at 1.8 to 2.0 Myrs). It followed the Tertiary Period. The Quaternary and the Tertiary Periods together make up the Cenozoic Era (the last 65 Myrs). The Quaternary is divided into two epochs, the Pleistocene and the Holocene. The Pleistocene (the Greek term for the most new) Epoch is the period from ca. 2.6 million years to 11,500 years (11.5 k yrs) before present (BP). The Holocene (Greek for entirely new or recent) Epoch began approximately about 11,500 years ago and continues to the present. The Quaternary Period is important because it is the geological period when the human evolution took place and it is also the geological period characterized by extraordinary changes in global climate such as the Ice Ages.

Although Ice Ages have occurred many times during the Earth's history, the Quaternary Period is in general considered to be the period of Ice Ages interspersed by warmer climates. The Quaternary Ice Ages were characterized by significant increase in the ice cover over the Earth's surface by up to 30%, lowering of snowline in mid-latitudes by up to 1 km and reduction of sea level by over 100 m.

In the following discussion on paleoclimate, with a focus will largely be on the past twenty thousand years (20 kyrs) is presented. For convenience, this time period is subdivided into late Pleistocene (~25 - 11.5 kyrs) and Holocene (~11.5 kyrs – the present). The Holocene is further subdivided into the early Holocene (~11.5 - 9 kyrs), mid-Holocene (~9 - 6 kyrs) and late Holocene (~ 6 kyrs – the present). Given the amplitude of human intervention on climate (and environment), there are groups that now suggest the use of the term *Anthropocene* to demarcate the period where the human activity affected climate at a level comparable to those in geological past. The onset of anthropocene is being currently debated and the suggestions range from the times of the beginning of the industrial revolution to the time when climatic/environmental changes due to human activity began to be discernible (Crutzen, 2002, Zalasiewicz *et al*., 2008).

In contrast to the early 20th century view of four Ice Ages, the present view is that about fifty Ice Ages (or glacial periods) and equal number of intervening warmer periods (the interglacial periods), have occurred during the last 2.6 million yrs. The evidence for these Ice Ages was provided by the variability in the $^{18}O/^{16}O$ isotopic ratios in the Foraminifera microfossils contained in sediments of deep oceans. The oxygen isotope signals were used to identify a number of glacial and interglacial periods during this time interval. The

Ice Ages were assigned even numbers (2, 4, 6 …) beginning with the last Ice Age (known as the Last Glacial Maximum or LGM), which occurred about 21,500 calendar years ago (21.5 ka, k and a are abbreviations for kilo (1000) and annum (or years), respectively). This is known as 'Oxygen Isotope Stage 2'. Similarly, the interglacial periods were given odd numbers (1, 3, 5…) starting with present interglacial as 'Oxygen Isotope Stage 1'. Within these cycles short term excursions can occur. One of the well known such excursion (the Younger Dryas cooling) occurred during the period 12,800-11500 years BP, possibly due to the break down of global thermohaline circulation that altered the energy transport across the world. This event implied an estimated global cooling of 5°C with peaks of up to 15°C. Another such event but not as severe, not yet well documented is now reported at ca. 8300 years ago and its universality is still being explored.

Reconstruction of Past Climate

Reconstruction of past climate needs:

1. A climate proxy, that is a physical, chemical or biological attribute/property of the natural system which enables quantification of the change in climate in the past, and
2. A chronometer to assign a time to this proxy. It is assumed that changes in the proxy/attribute with time in the system are only due to variation in climate.

An assumption in these reconstructions is that the basic processes in geo-environments remain the same through time. These together provide an understanding of the climate through time in the past. Curiously enough, most of the paleoclimatic reconstruction uses deviations/anomalies in a sequence. Thus, for example, presence of waterlain deposits in an otherwise dry region is an imprint of climatic change. Similarly, the presence of wind transported sand in an otherwise river dominated terrain indicates shift in climate, with respect to the present. Such anomalous records inform about climate related excursions during the past.

Paleo-records are of two kinds – one that are accumulative such as ocean and ice cores and others that are formed only under special configuration of climate and other parameters such as sediment supply, transport and preservation. Some of these sediment archives can be easily eroded by natural agencies of wind and water. Most of the sedimentary records on the land come in this category and therefore, by definition, these are discontinuous. Stated simply, in accumulative archives such as ocean cores, preservation of the record is generally assured *ab initio*, but for sedimentary records on continents, preservation is not guaranteed. Ocean cores, ice cores, tree rings and speleothems (deposits in limestone caves) are examples of accumulative records where the archive accumulates through time though in some cases the accumulation rate may vary with time. In contrast, all continental sedimentary archives such as river sediments, sand deposits and the like need a *window of opportunity* for their formation. The timing and duration of this window of opportunity is determined by the process of sediment production, the timing of its transport and its long-term preservation at the site of its deposition. It is the preserved record that is available for study. Thus in respect of continental archives, these issues make climate reconstruction over long time scales a difficult task though they are the only ones available to delineate the contemporary climate/ environmental processes that operated in the region. Given the complexity of climate, normally all records that are available in a region are examined and their convergence (as complete as possible), is sought for a reconstruction of climate state parameters such as wind vectors, temperature or rainfall through time.

Climate Proxies

Information about past climatic changes can be obtained from the study of climate-dependent natural processes. Such information is provided by paleoclimatic proxies, which are measurable parameters that provide quantitative or qualitative information about climatic and hydrological variables such as temperature, precipitation, runoff, discharge and sedimentation rates. Many types of natural archives have been used in paleoclimate reconstruction. The proxies range from depositional environment (sediment transported and laid down by wind vs. water, turbulent vs. calm water), sediment properties (grain size and its variability that inform about the energy levels and distance of transport), chemical changes (weathering indices or weathering products), pollen grains, oxygen and carbon isotopes on inorganic or organic carbon compounds and molecular changes that inform about the vegetation types and temperatures. The relationship of these proxies with climatic parameters is cardinal for the reconstruction of past climate and often contemporary data are used to calibrate the relationship. Further, their response time and thresholds to climatic shifts can range from being near instantaneous to periods spanning few centuries to several millennia. Some of the archives and climatic proxies are (Fig. 2):

Archives

- Fluvial sediments (transport by water)
- Marine sediments (from ocean bottom)
- Aeolian sediments (sediment transported by wind)
- Lacustrine (lake) and peat deposits
- Glacial moraines and proglacial deposits
- Ice Cores
- Corals
- Speleothems and tufas
- Tree rings

Proxies

- Grain size distribution/mineralogical changes
- Pollens
- Chemical composition
- Magnetic properties of minerals
- Plant macrofossils and their composition
- Foraminifera, diatoms, alkenones
- Isotopic composition (oxygen, carbon and hydrogen isotopes) of carbonates, organic matter

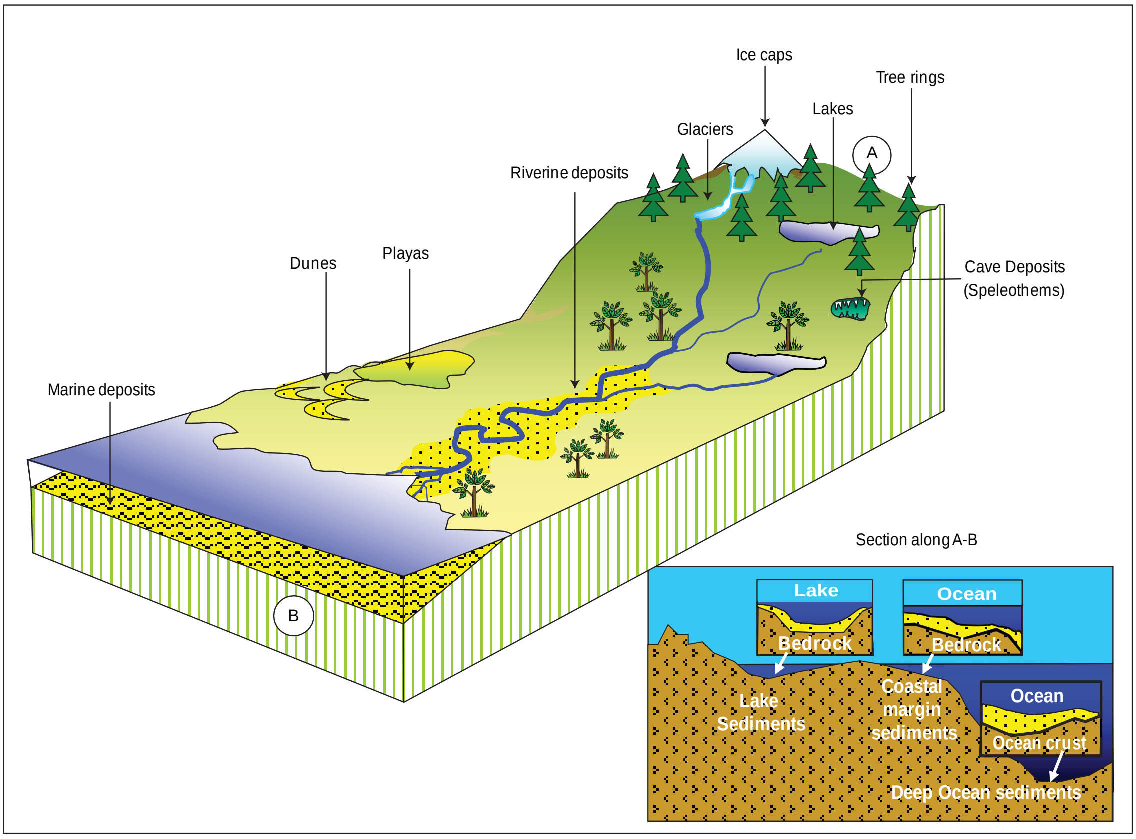

Fig. 2: Major archives used in the reconstruction of paleoclimate.

- C/N ratios of sediments
- Chromonids/ lichens
- Molecular proxies (lipids, constituents of leaf wax and marine organisms),
- Climate specific minerals (e.g. gypsum, that are formed under extreme environments)
- Tree line altitudes

The choice of a particular proxy depends on the period for which paleoclimate information is being retrieved, the site and availability of suitable material for extracting the proxy data. For the reconstruction of recent (the last few centuries and millennia) climatic changes, tree rings and corals, lake and ice-core records are commonly used. For reconstructing longer term climatic changes, ice cores, marine and lake repositories and various other sedimentary records have been used. As alluded to above, an important aspect of using continental sediments is that the record may have hiatus due to difficulties associated with formation and preservation of the sediment record. On land, the very agencies that create the record can also remove (erode) them. Sedimentary records on the land, therefore, are fragmentary and heterogeneously distributed in space and it is necessary to establish the completeness of the reconstructed records (as far as possible), using field surveys and dating of various sections to build a master, truly representative record of the region/drainage basin (called the type section that gives regional stratigraphy).

Chronometric Techniques

Assignment of time to an event recorded by a climate proxy is an important requirement of paleoclimatology. This requires the presence of a parameter (P) in a sample that changes with time at a known rate that can be explicitly defined by a mathematical function. This could be an annually added ring of a tree or the decay of a radioactive species. In general, any dating method can be understood by a simple example of a beaker being filled at a certain input drop rate (D) or being emptied at a known rate (L).

If the quantity of liquid in the beaker is A volume units, which varies with time, then the time (i.e. the age) needed to fill the beaker from the level A_i to A_f is given by the relation,

$$\text{Age} = \left|(A_f - A_i)\right| / \text{ (D or L)}$$

Where D is the drop rate (in units of volume/unit time) and L is the leak rate. Thus for example in the case of tree rings, the value A_i=0 (beginning of the ring growth), A_f is the total number of rings at the time the tree was cut and D is the rings added/year which is one year. So the ring count is a simple measure of the age of the tree. In contrast to this example where material/rings accumulate, radiocarbon method can be visualized as a case of leakey beaker. This is because on

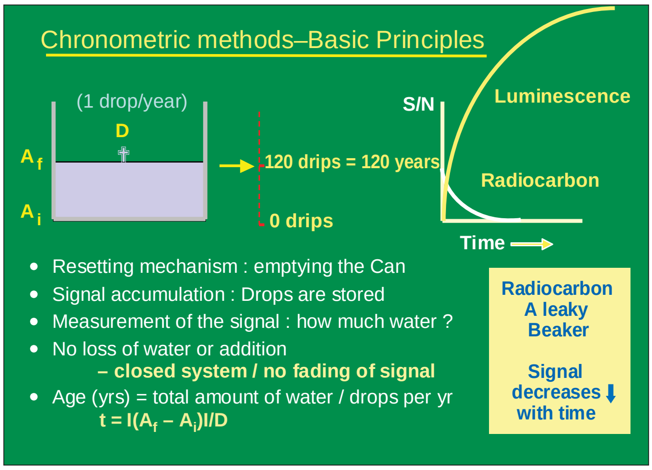

Fig. 3: The basic principle of a geochronological method. The approach on the left hand side is for a simple case. The variation in the signal with time for radiocarbon and luminescence are shown graphically on the right hand side. S/N implies signal to noise ratio, which increases with time in the case of luminescence and decreases with time in the case of radiocarbon.

death, the dead material can not exchange with atmosphere and its radiocarbon decays with its characteristic half life of 5730±40 years. The decay rate of radiocarbon defines the parameter L and the difference in the radiocarbon content from the initial value at the time of death to the present value enable calculation of the time it was removed from the exchange cycle. The form of the decay L is exponential and is built into the calculation. The case of luminescence dating or the tree ring is the case of a beaker being filled. In this case the luminescence signal is the difference between the initial luminescence and its final value and the rate of luminescence acquisition is proportional to the radioactivity of the sample, till saturation is reached. Saturation is akin to the beaker being totally filled beyond which limit the signal "spills over" and the analysis provides only a minimum age.

A key element for the success of any dating method is the validity of the assumption of a closed system i.e. the system had no unknown inputs or leakages during the time period under consideration and that the drop- (or the leak-) rate remained constant throughout and, if they did change then the magnitude and the style of change through time was exactly known. Typical examples could be the case of a missing ring or additional (false ring) in the case of tree rings and contamination of a radiocarbon sample with modern or old carbon. Documentation and understanding of these are crucial for establishing the accuracy and reliability of the ages. This makes it imperative that for every sample, the validity of closed system assumption is explicitly addressed to and its effects quantified.

An important aspect of chronometric methods is that they are seldom universally applicable. Each method requires a definitive set of samples formed during a given time interval where it can be applied, (Table 1). The choice of a method depends upon the sample and the likely range of the ages. Thus, for example, radiocarbon (^{14}C) method can be applied only to samples that contain carbon and those formed with in the past 50,000 years. Another important aspect to be borne in mind is that different methods generally date different events in the history of the same sample and due recognition of the time differences between various ages is needed for their proper interpretation. Thus, for example, when exposed to environment, a sedimentary stratum develops a soil layer and in such cases two ages can be obtained, viz. the age of the parent sediment stratum and the age of soil formed on it due to exposure to water and air. For such cases, radiocarbon analysis of the soil, A-horizon in it would provide the age of soil formation and at the same time, analysis of sediment in the B horizon using luminescence will give the age of deposition of the parent sediment. And, the two events can be time separated by several hundreds to thousands of years. Seeking concordance of the two events can be a futile exercise but if the analysis is made taking the soil processes in mind, it is possible to tease out more information on climatic changes.

The earliest efforts in geo-chronometry were based on the relative dating methods. For example, in stratigraphic sequences, the deeper the stratigraphic layer, older it is and this information itself provide relative ages. In this category, use is also made of chemical changes e.g. degeneration of organic residue in sedimentary strata to derive relative ages. These include methods such as fluorine to phosphate ratio (F/P) in ancient bones, sequential growth of hydration layer in obsidian glass (traversal of the wetting front through time). Amino acid racemization method that examines changes in the symmetry of some of the amino acids from left to right (levo to dextro) has also been used for dating organic materials on the premise that the temperature (and hence the racemization rate) remained constant through time.

Another method that has been used extensively is the reversals of magnetic polarity of the Earth through time. These reversals occur once about every few hundred thousand years to a million years. The magnetic vector of sediment grains deposited under gravity get oriented parallel to the earth's magnetic field direction. Thus, the magnetization of the sediments becomes normal or reversed (with respect to the present) depending on the direction of Earth's magnetic field at the time of their deposition. The global chronology of the reversal and normal events has been established using well constrained sequences with independent chronologic markers- both radiometric and fossil based. Thus a sediment sequence is a stack of magnetically normal and reversed sediment deposit. The magnetization of this stack is compared with global magnetic polarity sequence and this comparison is used to deduce the timing of the deposition of a particular layer by using a marker horizon of an independent age and by assuming a constant sedimentation rate. Given that reversals occur typically over million year time scales, the method offers poor resolution to be of use in recent Earth's climatic history.

Rutherford first conceived the idea of using natural radioactivity for dating way back in 1905. Early work of Joly (1908 a,b), Patterson (1937) (reviewed by Krishnaswami and Cochran, 2008) and later by Libby who discovered radiocarbon

Table 1: Methods for establishing ages of events

Dating Method	Age range	Dated events	Materials typically used for dating	Comment
Numerical Dating Methods				
Radiocarbon	>60 yrs to ~40,000 yrs	Time since the carbon in sample is isolated from atmosphere e.g. death of an organism	Wood, Charcoal, pollens, seeds, nuts, peat, ivory, bones, shells, organic debris in sediments	Sample-stratum correlation difficult, diagenesis, reworking, contamination can cause problems, calibration to calendar years needed
Luminescence	10 yrs to 10^6 yrs	Time when the sediment was last exposed to day light for several minutes, or heating of sediments to 400°C and mineral formation events	Quartz, feldspars, gypsum, carbonates, evaporites	Sample-strata correlation unambiguous but needs experimental rigor, time consuming analysis
Electron Spin Resonance	Few yrs to $>10^6$ yrs	Mineral formation and heating event	Silicates, carbonates, bones, organic materials	With the exception of few minerals, generally not suitable for very young sediments/ deposits
Cosmic ray produced isotopes	$10^3 - 10^6$ yrs	Exposure Ages of rock surface to cosmic rays	Rock surfaces of known geometries, silicates, sediments	Needs an assurance for constant exposure geometry which is not easy to satisfy
Potassium/ Argon-Argon dating	$>10^6$yrs	Rocks, mineral formation	Volcanic ash, lava flows feldspars, last heating events	–
U-Th series radionuclide	$>10^4$ yrs	Precipitation of carbonates	Carbonates	Needs pure and pristine carbonates
Chemical Dating Methods				
Hydration, fluorine-uranium and nitrogen uptake methods	100 yrs to million yrs	Fracturing of obsidian, death of organism and burial	Obsidian, bones, teeth	Qualitative methods, large differences in ages from same stratum
Amino acid recemization	$10 - 10^6$ yrs	Death and burial of organism	Bones, teeth, ivory	Assumption of a constant recemization rate can not be verified easily, particularly for samples from the tropics
Biostratigraphy	Most of the geological past	Sediment strata correlated on the basis of index fossils	Foraminifer, Ammonite	Assumes that the presence of the same fossil in a primary context, independent of the type of deposits indicates the same age
Annual Layer Counting Methods				
Dendro-chronology	Recent to ~ 10,000 yrs	Tree cutting events	Trees that add a ring annually e.g. oaks, pines	Needs long-term chronology for trees, floating chronologies needs considerable rigor to establish their correlations, missing rings, false rings
Sediments, varves	Up to a few thousand years	Lake sediments, speleothems and similar carbonate deposits	Lakes that have annual distinct layers, speleothems, corals	Missing layers not easily recognized, and at times secondary calibration needed that leads to a compromise on annual resolution

dating in the late 1940s, laid the foundations of radiometric dating (Libby, 1952). Other developments in dating methods followed and the past three decades have witnessed considerable improvements on understanding the range and applicability of several dating methods. Increasing sophistication in instrumentation has led to newer developments and, at the same time, brought to light newer problems that were not even considered till recently. Thus, it is prudent to suggest that multiple dating studies on same stratum alone can ensure a reliable dating. A reliable age is the age where multiple dating evidences, converge taking due cognizance of the processes and events being dated by each of the techniques.

Most of the research in paleoclimatology is now based on high resolution numerical chronometry provided by either of radiocarbon, luminescence and/or Uranium series methods. In addition, use of annually added tree rings (dendrochronology), annually added layers (corals, speleothems, varves), can provide annual scale resolution based on ring (layer) counting. *Dendrochronology* depends on the fact that some species of trees add a ring every year and hence a count of the number of rings provides the age of the tree till the date the tree was cut and/or stopped growing. Though a simple forward method, it requires appropriate information on the date the tree was cut and multiple analyses of cores through the same trunk to ensure that no false ring or missing rings are counted. In the case of a piece of wood for which the date of cutting is not known a floating ring chronology is created and matched with standard ring patterns for the region and the tree type to arrive at an age. This needs considerable statistical rigor.

The *radiocarbon method* is based on the fact that cosmic ray produced radiocarbon (^{14}C) in the atmosphere, though is heavier compared to its stable counter parts ^{12}C and ^{13}C, is chemically similar to them. This forms $^{14}CO_2$, enters the carbon cycle and gets dispersed globally. ^{14}C enters the biosphere and hydrosphere through photosynthesis, gas exchange and as dissolved carbonates. The radiocarbon concentration of the atmosphere is at equilibrium with respect to exchange with carbon from the hydrosphere and biosphere. Carbon compounds formed by exchange with atmosphere are labeled with radiocarbon with the same $^{14}C/^{12}C$ ratio as the atmosphere, except for some minor isotopic fractionation. On removal (i.e. death) of the sample from this exchange cycle, its radiocarbon content depletes due to radioactive decay, with a half-life of 5730±40 years. The ratio of the residual $^{14}C/^{12}C$ in the sample with the atmospheric $^{14}C/^{12}C$ provides the time elapsed since the removal of the sample from the atmospheric exchange cycle. All samples containing carbon in any form can be dated by radiocarbon but a few caveats apply. These relate to the potential exchange of carbon in the samples with "dead carbon" (that dilute its radiocarbon concentration) or "modern carbon" (that adds younger carbon) which make the ages erroneous. The second important aspect is that the atmospheric radiocarbon production has not remained constant through time due to variations in the cosmic ray flux. Correction for this is done through radiocarbon measurements in tree rings, varves (annually layered) marine sediment, lake sediments, corals, speleothems and ice cores, whose ages are precisely known by independent and secured methods. Presently this correction is established for the past about 14,000 years and for older samples that some spot calibrations up to 45,000 years are available. Only after the calibration, the radiocarbon age corresponds to calendar age.

A technological advance that occurred about three decades ago is the use of Accelerator Mass Spectrometry (AMS) for measurement of long lived cosmic ray produced isotopes such as ^{14}C (and other radioisotopes such as ^{10}Be and ^{36}Cl). This technique counts the radiocarbon atoms (instead of decays as in radiation detectors). This has resulted in a significant enhancement in the sensitivity of measurements by several orders of magnitude to the extent that it is now possible to determine radiocarbon age using milligram size samples (e.g. single pollen grain). Interpretation of radiocarbon ages of organic/inorganic matter in sediments requires the establishment of the relationship of organic fraction and the sediment strata that it belongs to. It is likely that the organic matter was removed from the atmospheric exchange much before its incorporation into the sediment layer. This could result in a systematic age offset and hence erroneous paleoclimatic reconstruction. The decay of radiocarbon implies that with age, the signal decreases and presently typical limit of dating is about 40,000 years before present (BP). Normally the precision of measurement is high (~ 1%) but this is compromised somewhat during the calibration of ages to get calendar years. Ages with measurement precision of 1% at 18,000 years corresponds to a calibrated age of 21,700 with an error of about 500 years. Such calibration can be done using calibration curves that are based on precise measurements of radiocarbon content of annual tree rings. The ^{14}C method has been employed to ascertain the age of wood, charcoal, shells, humus, gastropods, peat, carbonaceous clays and calcrete (*kankar*). Normally radioacarbon ages are reported with 1950 base line and carry a BP notation with age. BP implies before present and relate to the year 1950 as the base line. This is because over ground nuclear weapons testing programs during the 1950's and 1969's released large amounts of artificially produced radiocarbon and other radioactivities such as ^{137}Cs to the environment. These have caused significant perturbation in the radiocarbon inventory, particularly of the atmosphere, and hamper the measurement. On the positive side, scientists have used this transient input or radiocarbon in the atmosphere to study carbon exchange rate between atmosphere, oceans, lakes etc., an aspect that has helped refine the understanding of carbon cycle.

A more recent development is *Luminescence dating*. This method uses natural ubiquitous minerals such as quartz and feldspars to establish ages of sediment layers. The ages are determined via the measurement of radiation damage suffered by these minerals due to irradiation from environmental radiation. The natural environmental radiation comprises alpha, beta and gamma rays from the decay of naturally occurring uranium, thorium and potassium. In addition there is also a minor contribution from cosmic rays. The radiation damage process is basically ionization of minerals by alphas, betas or gammas resulting in creation of free charges that move in the lattice, some of which eventually get trapped in the lattice at defects deficient in appropriate charges. Occasional displacement of atoms from their lattice sites can also occur. In some cases, the trapped charges can reside in the trapping centers for several thousands to millions of years. An external energy stimulus in the form of heating to 400°C or light exposure however can detrap the charges instantaneously and be made free again. Some of the free charges go to another set of defect sites called luminescence centers and are captured and produce luminescence in the process. It turns out that the entire process, though complex, still results in proportionality of luminescence intensity and radiation exposure. Thus, the measured luminescence in a geological sample is a measure of the total radiation dose received by it since burial. Appropriate laboratory measurements using calibrated radiation sources permit conversion of luminescence intensity to radiation dose. This is designated as paleodose. Under the assumption that the paleodose at the burial time was zero, this when divided by annual irradiation rate (dose rate) gives the age of the sample. This is determined by measuring the elemental concentration of U, Th and K in the sample and by using appropriate laws of physics. The method is versatile in that it can provide ages for a variety of events ranging from mineral precipitation (gypsum and carbonates), sediment deposition (almost all reservoirs) and thermal events (sediments heated in contact with lava flows or forest fires). In all these cases, heating or daylight exposure ensures that luminescence level at the time of burial of sediment is zero or near zero and the paleodose truly reflects the accumulated luminescence since burial. Recent advances in instrumentation enable dating of single grains of 100-200 μm diameters and this offers an opportunity of measuring a large number of single grains and analyzing samples with complex depositional environments. The applicability of this method, typically range from a few years to several hundred thousand years (million years or more in selected cases). This method, therefore, fills up the entire time domain of dating the recent Earth history spanning the past million years of so.

Other techniques, such as *Uranium series disequilibrium methods*, depend upon preferential removal of a radioactive member from the decay chain and then rebuilding of the decay chain towards radioactive equilibrium. The equilibrium methods find application for dating archives such as marine sediments, corals and continental carbonates. Recent advances include in the measurement of longer lived U, Th and Ra isotopes based on mass spectrometric techniques. The use of this method in continental sequences requires pure carbonates, which is rare in nature. For impure carbonates, errors due to correction for detritus, digenetic alteration, can be significant and, need careful sampling strategy and modeling to derive ages.

2. PALEOCLIMATE IN THE INDIAN CONTEXT

In the Indian context, perhaps the most important single climate factor is the monsoon that determines the lives, ecology and economics of the region. Agriculture critically depends on water received during the summer monsoon and even the winter crops use the residual moisture from summer rainfall. To an extent, paleoclimatology in the Indian context is a synonym for the reconstruction of monsoon through time.

The Indian Monsoon

The Indian subcontinent is one of the largest monsoon-dominated regions in the world (Fig. 4). The term 'monsoon' is from the Arabic word '*mausam*' meaning 'season'. In the Indian context, it basically represents the seasonal reversal of wind direction over the subcontinent. During summer (June-August), the southwesterly winds (the summer monsoon) pick up moisture from the oceans, travel to land and

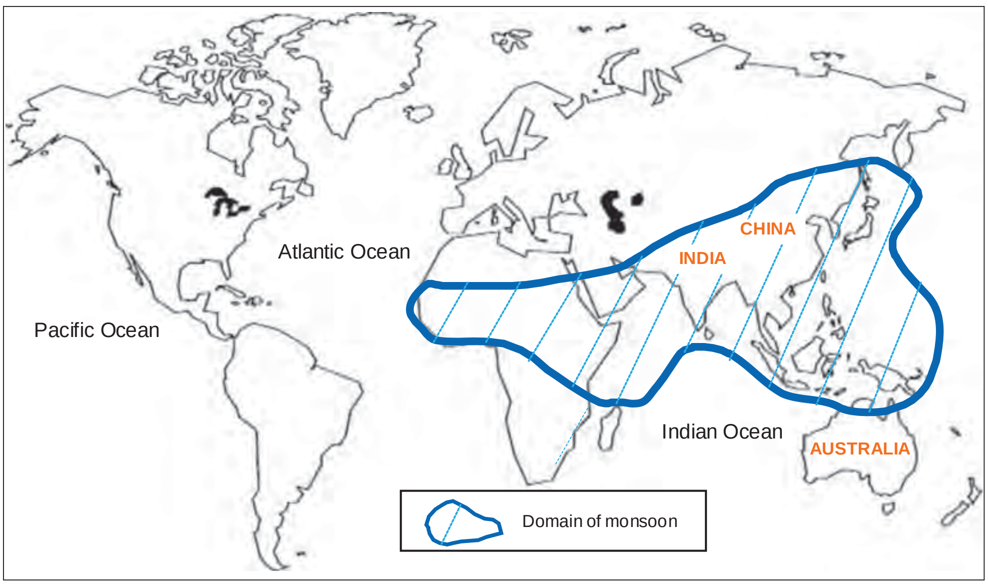

Fig. 4: The Monsoon dominated regions of the world. Redrawn from Williams et al. (2006).

precipitate their moisture over the region. During winter (December-February), however, the monsoon winds are dry and variable, blowing from the northeast, from land to sea. Most parts of the Indian region receive a major portion of their annual rainfall during the summer or southwest (SW) monsoon.

Differential warming of South Asia and the surrounding ocean causes monsoons. The areas of the northern and central Indian subcontinent heats up during the northern summer season. This is responsible for development of a low pressure area over the northern and central Indian subcontinent. The moisture-laden winds from the Indian Ocean move in to fill this void via Bay of Bengal and the Arabian Sea. The monsoon winds are confined to the subcontinent and are not allowed to carry the moisture to central Asia by the mighty Himalay Mountains, which form a physical barrier (Fig. 5).

The average summer monsoon rainfall over India is about 850 mm and accounts for nearly three-fourths of the mean annual rainfall of ~1180 mm. The monsoon rainfall, however, is not uniformly distributed over the subcontinent. The eastern parts receive up to 10,000 mm of rain (Shillong plateau), the western parts (Thar desert) receive less than 150 mm of rain during the same southwest monsoon season. The spatial variation is related largely to atmospheric circulation patterns that determine moisture transport and its delivery to land under suitable conditions. Similarly, there is also considerable temporal variation in the monsoon rainfall (Fig. 6). For example, 1917 and 1961 were excess monsoon years (>1000 mm or +18%) and 2002, 1987, 1972, 1918, 1899 and 1877 were major deficient monsoon years (<700 m or –18%) (Fig. 6).

The Indian monsoon along with Chinese monsoon plays an important role in modulating the global climate as well as controlling the global hydrologic cycle. Analyses of over 130 years of meteorological data have revealed the following characteristics about the Indian summer monsoon.

1. The monsoon is a stable atmospheric phenomenon and has never failed completely and, perhaps it never will. There has been no year with out any rainfall and perhaps, will never be.
2. Despite this robustness of monsoon as a system, significant spatial and temporal variability in rainfall exists. This is generally within ± 30% of the mean. The droughts are often caused by the variability in the timing and duration of rainfall events. Thus a rainfall spread over a short time may cause flood but the same spread over a longer span may result in a drought. Statements on annual rainfall therefore have no meaning.

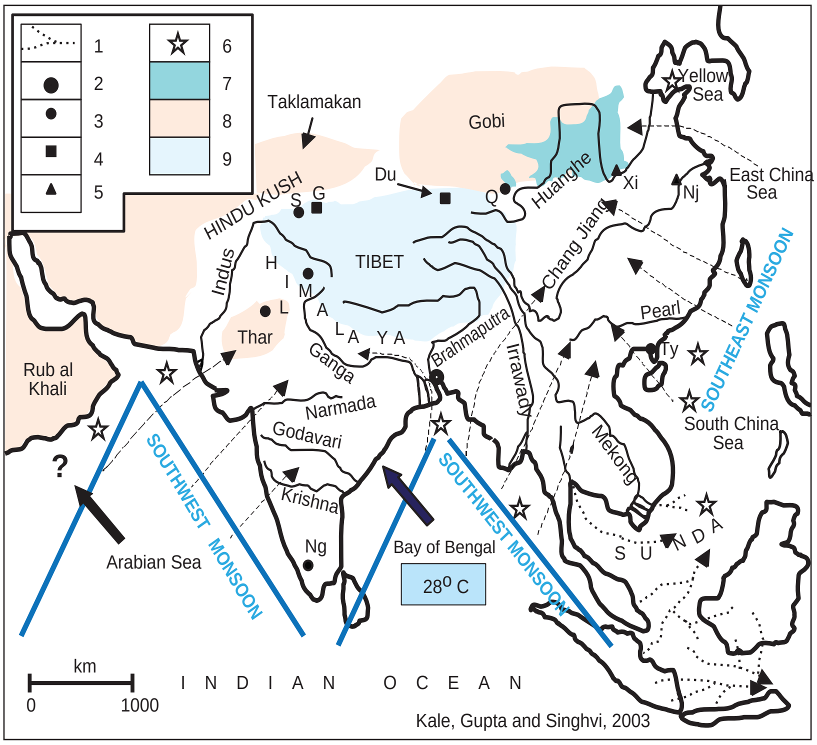

Fig. 5: The monsoon winds shown by dashed lines and the broken arrows show the wind patterns for the months of June to September. Thermal stratification of the Bay of Bengal is an important aspect and observations suggests that sea surface temperatures of >28°C are needed for rainfall to occur. It is also interesting to note that although Bay of Bengal and Arabian Sea are nearly identical in terms of geometry (blue arrows), the Bay of Bengal, by virtue of being stratified with high sea surface temperature provides rainfall to India. The Arabian Sea is much cooler and hence does not provide rain to the Arabian desertic region (thick black arrows). Key sites where paleoclimate reconstructions have been done are also given. These are: 1 = Extinct drainage of Sundaland, 2 = Borehole sites, 3 = Lake/peat sites, 4 = Ice core sites, 5 = fluvial/flood sites, 6 = Deep sea core sites, 7 = Loess Plateau, 8 = Deserts, 9 = Qinghai-Tibetan Plateau, Du = Dunde ice cap, G = Guliya ice cap, L = Lunkaransar Lake, Ng = Nilgiri, Nj = Nanjing flood site, Q = Qinghai Lake, S = Sumxi Co, Ty = Tianyan Lake, Xi = Xiaolangdi paleofloods site, (modified from Kale et al., 2003).

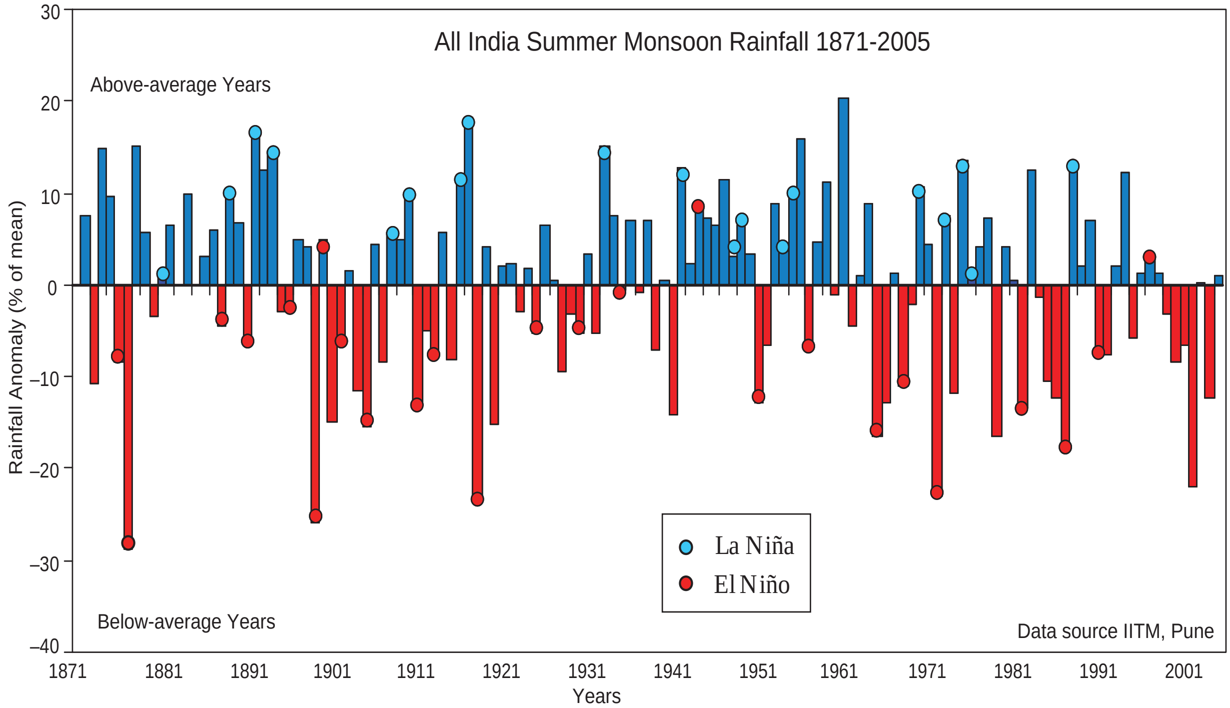

Fig. 6: Time series plot showing the interannual deviation in monsoon rainfall over India for the period between 1871 and 2005.

3. Low pressure systems originating over the Bay of Bengal and the Arabian Sea are important sources of moisture during the monsoon season.

Since the early 20th century, the ENSO (El Niño/Southern Oscillation) was considered to be the largest climatic forcing of interannual monsoon variability. Poor monsoon was found to be associated with warm Elnino events (Fig. 6). Monsoon depends on several parameters which make its prediction, a difficult task. Table 2 provides a list of parameters that have been used for monsoon prediction. These are based on observation over the past century. However, analysis of recent data shows that this interrelation between some of these parameters has broken down in recent decades (Krishna Kumar *et al*., 1999).

Analysis of rainfall data available for over hundred years has shown that the Indian monsoon rainfall has no significant long-term trend, although epochal variations are known. Some recent studies have shown contrasting results of a decreasing trend in the frequency of tropical cyclones and monsoon depressions and significant rising trends in the frequency and magnitude of extreme rainfall events over central India between 1951 and 2000 (Goswami *et al*., 2006).

The Need to Study Past Monsoon

The instrumental records of monsoon rainfall approximately span the past 140 years (since 1871). Such a small duration of record is not sufficient to capture all the frequencies of variation in monsoon. Reconstruction of the past records enable creation of longer time series of climate record such that a more complete description of the temporal long-term variations of monsoon is available for the deduction of all the frequencies that determine its behavior. These frequencies basically reflect various forcing functions and feedbacks in the climate system that is difficult to be assessed and quantified using first principles. The basic reason, therefore, for studying the past monsoon behavior is that the past performance of the monsoon is likely to provide vital inputs for constructing future scenarios. The reasons are:

a) Monsoon is the lifeline of the agrarian economy of the country. Though it is a stable atmospheric system and has never totally failed, erratic distribution of precipitation and, its spatial and temporal distribution can contribute to significant changes in food production and hydrological systems. Thus, for example, a reduction/enhancement in total amount of rainfall by a mere 20 to 30% in a season can cause agricultural droughts or severe floods. Even minor shifts in rainfall pattern (± 10%) during the monsoon season can significantly affect the agricultural productivity and water availability. The summer crops directly depend on summer monsoon rainfall and the winter crops in a major part of the country also depend on the residual moisture left by the summer rainfall. The irrigation system also depends on the water accumulated from the summer rains.

b) In India, the prediction of monsoon has largely been based on a statistical correlation of various parameters (Table 2) that most likely control the heat and moisture fluxes during the season, leading to monsoon. However, it is not known if these parameters are time invariant and any uncertainties or errors in their correlation with the monsoon rainfall can lead to errors in predictions. Validation and determination of the domain and uniqueness of parameters is needed for better predictive skills. This in turn requires long-term data of climate

Table 2: Parameter used for monsoon rainfall predictions

Sr. No.	Model Parameters	Months	Correlation Coefficient
1.	El Nino (Previous Year)	July+August+September	+0.42
2.	Eurasian Snow Cover	December	–0.46
3.	NW Europe Temp	January	+0.45
4.	Europe Pressure Gradient	January	+0.42
5.	50 hPa Wind Pattern	January+February	–0.50
6.	Arabian Sea SST	January+February	+0.55
7.	E Asia Pressure	February+March	+0.61
8.	S Indian Ocean SST	March	+0.52
9.	Nino 3+4 SST Trend	April-May June; January-February March	–0.46
10.	S Indian Ocean 850 hPa Z Wind	June	–0.45

state parameters, i.e. rainfall and temperature. Reconstruction of the past is the only way to create long time series of climate state that can be used to better inform the climate modeling efforts.

c) A linked issue is the determination of style and amplitude of changes in the monsoon system by human induced factors such as global warming, ozone depletion, deforestation and desertification. The knowledge of past climates (*paleoclimates*) and hydrology (*paleohydrology*) is critical in this regard, since these provide vital baseline data for much longer time scales.

d) It is now being increasingly realized that on account of their energetics, the monsoon, may be the driver of climatic change on a global scale. This by itself needs a better elucidation of magnitude and phase of changes in monsoon with those in global climatic system as documented by ice cores and deep sea cores.

The Antiquity of the Indian Monsoon

Numerous marine proxy records from the northern Indian Ocean and loess (wind blown dust) records from China indicate that the present-day South Asian monsoon system was established about 8 million years ago. The rise of the Himalay Mountains and Tibetan Plateau (beyond a critical height) about ca. 8-10 million years ago is believed to be the main cause of the establishment of the monsoon system over the Indian subcontinent. Another view that has been suggested in recent years is that the present monsoon system is the consequence of global cooling and the increase in volume of the Antarctic ice sheets and the associated strengthening of the wind regimes about 8-10 Ma (Gupta *et al*., 2004).

More recent evidence based on high resolution analysis of marine cores suggests that monsoon during the past 10, 000 years was affected by the changes in the solar output. Studies reveal that weak summer monsoon correlate with reduced solar output (Agnihotri *et al*., 2003, Gupta *et al*., 2005). It is, however, to be established if this observation on monsoon winds could be directly translated to rainfall and its spatial distribution on the land.

3. STUDIES ON PALEOCLIMATE OF INDIA AND ADJACENT REGIONS

Ice Cores

Ice accumulated from snowfall over several millennia in high mountains and polar regions has been studied by scientists to reconstruct past climate. The ice core, which is a core sample obtained by drilling through thick ice, contains wind-blown dust and bubbles of atmospheric gases. The analysis of dust and trapped air, chemical species such as sulphates and oxygen isotopes of ice enable reconstruction of climate almost with an annual resolution record of the climate at the time of ice accumulation. Ice cores from the polar ice caps of Antarctica and Greenland have provided a wealth of information about global climate and environmental changes over more than a full glacial-interglacial cycle. The ice-core records extend back to more than 800,000 years. Three ice caps on the Tibetan Plateau, namely, Dundee, Guliya and Dasuopu (Fig. 5) have provided evidence of noteworthy fluctuations in the intensity of the Indian monsoon. The following major observations emerge from the study of Tibetan ice-cores (Thompson *et al*., 1989, 1997, 2000).

1. The last glacial stage was characterized by colder, wetter and dustier conditions compared to the preceding stages.
2. Early to mid-Holocene (6000 to 9000 yrs) experienced more moist condition due to the intensification of monsoon.
3. During the last millennium many periods of drought have been indicated, but none have been of greater intensity than the greatest recorded drought during 1790 to 1796 A.D.
4. A strong 20^{th}-century warming trend is apparent from the ice-core records.

In India, considerable emphasis is now being placed on the study of ice cores both from glaciers and Antarctic. Figure 7 presents a field view of ice core being taken at the Indian Station in Antarctica.

Fig. 7: *Ice coring by the Indian expedition in Antarctic. Kindly provided by Dr. R.Asthana of GSI, Faridabad.*

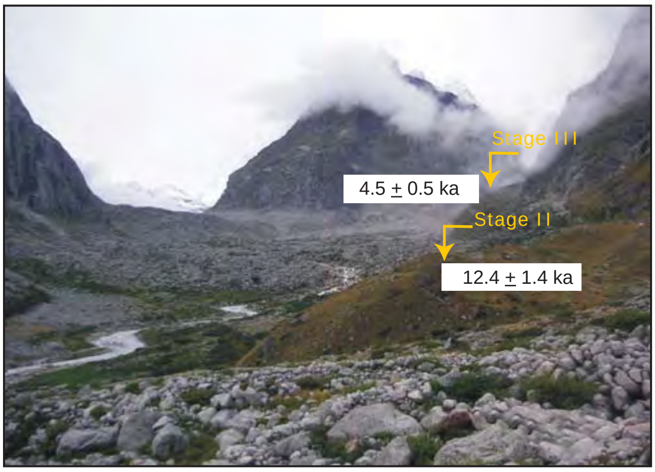

Fig. 8: A panoramic view of the Satopanth and Bhagirathi glaciers (in the back ground) and the moraines at their confluence near Badrinath. A drumlin (Stage II) and lateral morine (Stage –III) are dated to 12400 yrs (12.4ka) and 4500 years (4.5ka) respectively. Kindly provided by Dr. N.Juyal PRL.

Glaciers and Glacial Deposits

The highest concentration of glaciers outside of the Polar Regions is in the Himalay and Transhimalay Mountains. Glaciers extend and descend to lower altitudes under a combination of suitable conditions of lower temperatures and increased precipitation. The geological record of such lowering is provided by debris brought in by advancing glaciers and left behind during retreat. This debris can be recognized in the field as heap of mix lithologies and rock sizes and can be dated by techniques such as luminescence and insitu produced cosmogenic radionuclides. These have often been used to infer past episodes of glacial advances indicating the extent of lowering of equilibrium line altitude (ELA). In the past ELA was taken as a direct surrogate for temperature. However recent studies have provided a noteworthy inference that during the past 100,000 years it was the marine isotope stage (MIS) MIS 4 (~80 - 65 k yrs) that witnessed a larger extension of glaciers than the MIS 2 (~25 - 15 k yrs), the last glacial maximum. Given that it is known that MIS 2 was the coolest period in the past 100, 000 years, it appears that increased precipitation caused higher extension during MIS 4 despite a somewhat higher temperature compared to MIS 2.

The dated records of such events from the glaciers in Himalaya are few. One of the recent studies have been in the Upper Alaknanda basin, beyond Badrinath, where three stages of glacial advances have been documented (Fig. 8).

The oldest stages (I) reached south of Badrinath at 3000m asl (not seen in the picture). Stage II, dated indirectly of the last glacial maximum extended to 3550 m asl and the retreat of glacier after the glacial maximum (~21.5 kyrs) was temporarily halted around 12.5 kyrs as is seen in the from of the drumlins (cigar shaped debris heap). This reflected the effects of Younger Dryas event of global cooling. Stage III dated to 4.5 ka was terminated below the present day snout position at ~ 3700 m. Such work on long-term record of glaciers has been limited due partly to lack of logistics of raising and transporting long cores and partly due to the absence of dating possibilities. Studies on relict lakes in the region formed due to natural damming by tributary glaciers have provided rich data on the monsoon fluctuation and have been described in subsequent sections.

Marine Sediments

Rivers and atmosphere carry and deposit large amount of sediments into the oceans every year and deposit them on the ocean floor. In addition, calcareous and siliceous skeletons of microorganisms resulting from the biogenic production in the ocean are also deposited on the ocean floor. The nature and abundance of organic and inorganic materials within the sediments provide information about the climatic conditions prevailing on land and biogenic productivity in surface layers of the ocean at the time of sediment deposition. Because marine micro-organisms (such as foraminifera) have a limited range of habitable conditions (determined by salinity and temperature) their presence/abundance within the marine sediment layers is used to infer about the past climatic conditions.

In the last few decades, several marine cores have been obtained from the Bay of Bengal and the Arabian Sea to study and reconstruct changes in the monsoon strength over the Indian subcontinent during the last several thousands of years. Using *Globigerina Bulloides*, a foramineferal proxy, long-term and short-term events of change in the monsoon wind strength have been inferred. This is because, near the coast of Oman and Somalia the monsoon winds move surface waters away from the coasts to be replaced by cooler waters from deeper depths. In these cooler waters, specific species of foraminifera (e.g. *Globogerina bulloides*) grow. Their abundance is corelated to the upwelling intensity which in turn is controlled by monsoon wind intensity. These cold water foraminifera are deposited in contemporary sediments and provide a means to reconstruct monsoon wind strengths. In addition to the abundance of forams, the oxygen isotope compositions of their calcareous shells have been used extensively to decipher temperature/salinity conditions of the water where they grew. These oxygen isotope data are often supplemented by other proxies, such as trace element ratios with reference to Ca (e.g. Ba/Ca, ratio, etc.). The habitat conditions are inferred from the oxygen isotopic ratios, and also other elemental proxies are used to deduce contemporary environments. The calcareous sediment cores are now-a-days dated using Accelerator Mass Spectrometric radiocarbon measurement of foraminifer species. A weakness of the radiocarbon ages has been the uncertainty in the reservoir ages and this can cause finite systematic errors of a few hundred years. Several studies on monsoon have been carried out on samples from sediment cores near the Oman margin and near the coastal regions of the western Arabian Sea. In recent years, studies on sediment cores collected from the eastern Arabian Sea (along with AMS ^{14}C dates on foraminifers) use proxies such as abundance of organic carbon and its $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ of selected forams, and major and minor element concentrations. The main rationale in these reconstructions is the fact that monsoon winds exert a surfacial drag on the warm surface waters and move them away from coasts, making deeper (and cooler waters) to upwell. These results in appearance of specific temperature foraminifera on the surface which eventually get buried. Stronger monsoon winds result in stronger upwelling and hence in increased abundance of the cooler species appearing in the contemporary sediments. An example of a recent reconstruction is provided in Figure 9.

Studies on marine sediment cores in the Indian context have enabled the following major inferences,

1. The monsoon intensity shows a steady increase from ~ 1700 AD to present, based on high resolution study of a core (~ 20 yr resolution). The monsoon intensity pattern during the past millennium matches closely with that of Total Solar Irradiance (TSI). The monsoon intensity shows periodicities of ~ 200, ~ 110, ~ 70 and ~55 years, closely matching the reported periodicities in TSI. This has led to the inference that on centennial scale solar variability is a key regulating factor of SW monsoon intensity.

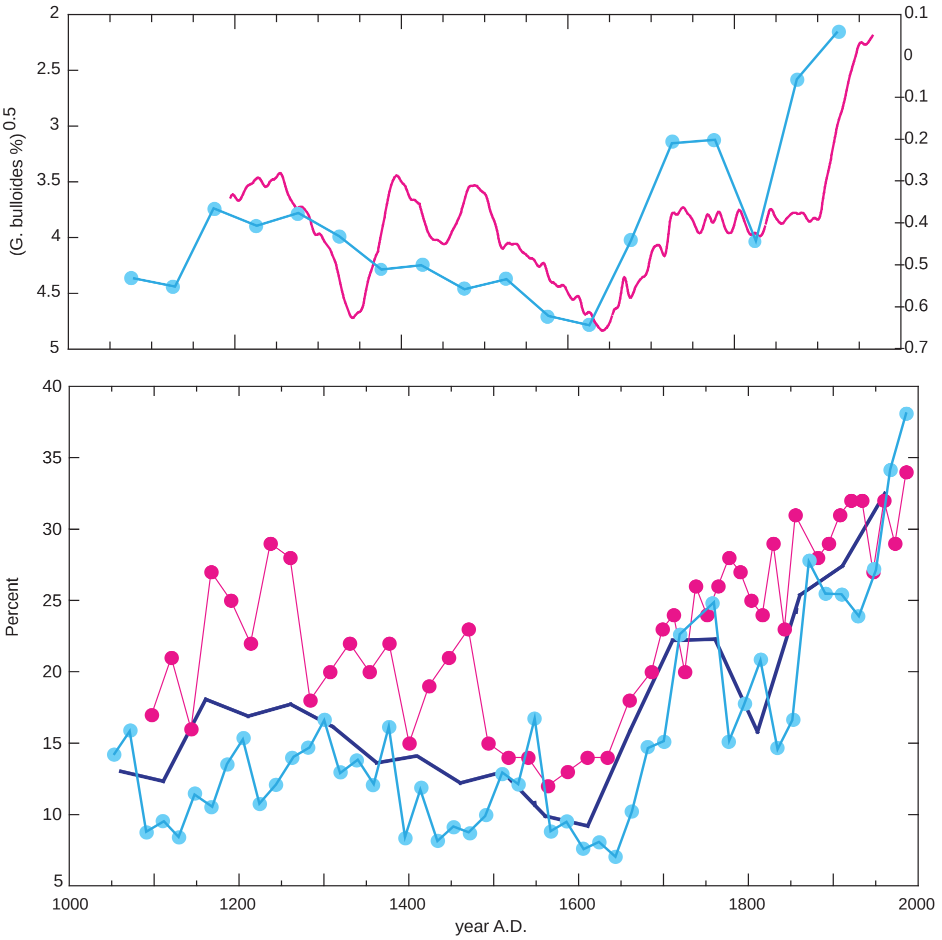

Fig. 9: A) Time series of northern hemisphere land temperature variations (50 year running average), from Mann, et al., 2008, and the variations in the index linearly related to the Arabian Sea summer monsoon wind speed (the square root of G. bulloides composite percentages relative to 1975). B) Time series of G. bulloides abundance from box core RC2730 (solid symbol) and RC2735 (open symbol), and the composite produced by averaging within 50 year intervals. Kindly provided by Dr. D. Anderson.

2. On longer time scales (~ 10 kyrs BP) monsoon steadily increased from 10 to 2 kyrs with significant periodicities at ~ 1400 and ~ 700 years. These periodicities coincide with the Bond cycle (high latitude, ~ 1400 years) and the ~770 yr cycles of South Asian monsoon. These results bring out the ubiquitous nature of climate variability on millennial time scale during the Holocene Epoch.
3. During ~ 42 to 20 kyrs, surface productivity (a proxy of monsoon) was lower than that during the Holocene with a minimum at LGM. Subsequently, there was a steady increase between ~ 20 and ~ 10 kyrs, attributable to an increase in the summer insolation. The productivity continued to increase up to ~ 2 kyrs, the increase however was lower during 10 to 2 kyrs period relative to that in 20 to 10 kyrs.

These studies highlight the utility of sediment cores from the Arabian Sea to study paleomonsoon and its variability over different time scales and resolution. It is however appropriate to mention that marine sediments provide a proxy to monsoon winds and not of actual rainfall on the land. This aspect has often been missed in interpreting higher upwelling to higher rainfall and is discussed in a later section.

Additional information from the Bengal Fan has also accrued. Here the major information comes from the sediment flux from large rivers such as the Ganga and the Brahmaputra, which is linked to the rainfall amount and once again detailed correlation of changes in sediment flux and other attributes indicate long-term changes in monsoon strength.

Some of the key inferences that have come out from these studies are (Fig. 10):

1. During the Last Glacial Maximum or LGM (21,500 calibrated years before present or cal. yrs BP), cold and dry conditions prevailed over the Indian subcontinent and the southwest monsoon was weak. This is inferred by the presence of warmer surface dwelling species in the marine cores.
2. The monsoon strength increased in two steps at 15,300-14,700 and 11,500-10,800 cal. yrs BP, as was seen by the increase of deeper dwelling species.
3. Strengthening of summer monsoon and related precipitation high occurred during early Holocene (between 9500 and 5500 years BP). Discharge and sediment inputs to the Bay of Bengal and the Arabian Sea from the Himalayan and Peninsular rivers increased significantly during this early Holocene monsoon optimum (climate optimum).
4. Short duration (few centuries) weaker monsoon conditions occurred at about 8,200, 6,000, and 5,000 – 4,300 and 2,000 cal. yrs BP.

In an interesting study of the ancient texts such as Arthashastra, Nirukta, Ramayana etc, along with modern scientific data, it was seen that the periods of water stress as inferred from the texts seem to correlate with the periods of low monsoon winds as inferred from the oceanic records (Pandey *et al.* 2003; Fig. 11).

Riverine Sediments

Terrestrial paleoclimatic proxies included riverine deposits and flood sediments. Sediment laminations or layers along with grain size distribution inform about the sedimentation style and energetics and their amplitude. These investigations include stratigraphical studies of the deposits in naturally exposed bank or gully sections or in trenches. In addition, borehole data are also used to understand the changes in the deposition style and river regime conditions. Charcoal, organic matter and mineral grains trapped in sediments are used to date the sediments using radiocarbon and luminescence techniques. Remains of flora and fauna within the fluvial deposits can indicate changes in past environments.

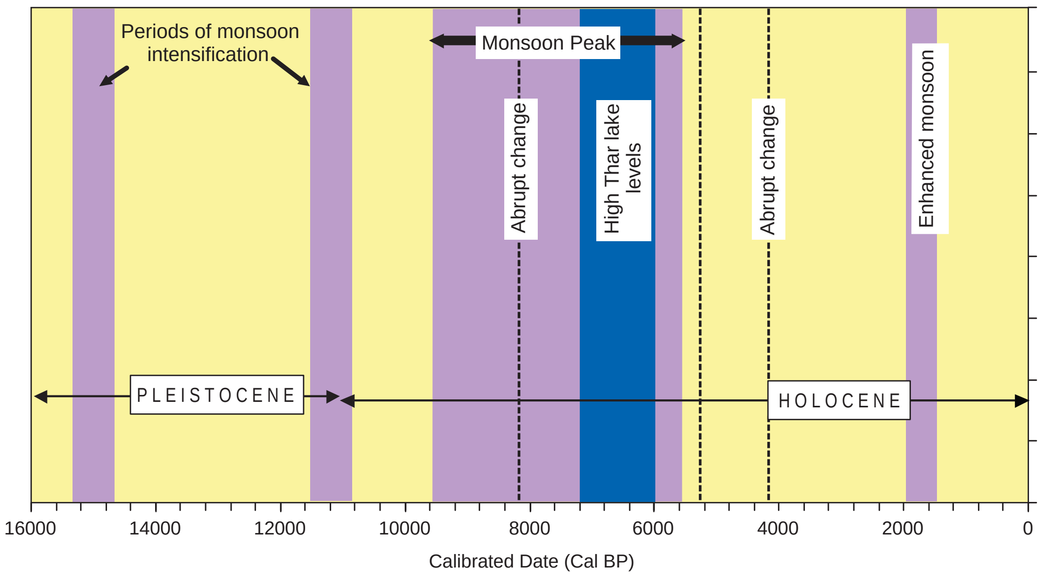

Fig. 10: Summary of major changes in monsoon condition during the past 15,000 cal years BP. Prepared by Dr. V.S. Kale.

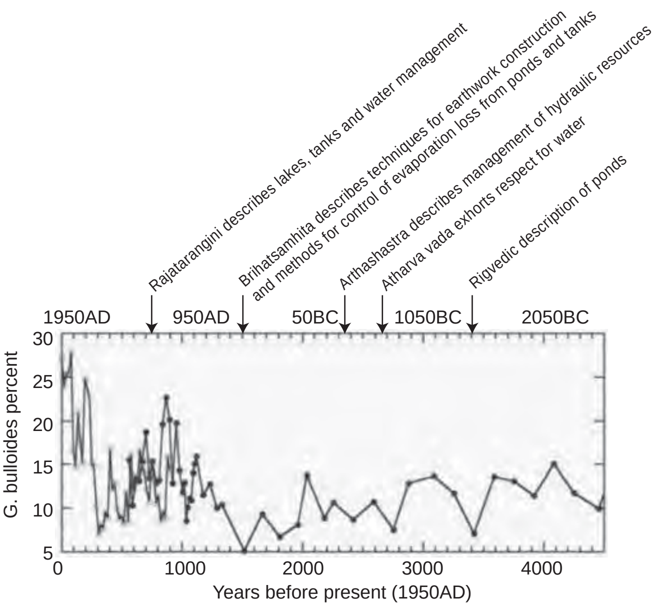

Fig. 11: Using percentage of plankton Globigerina Bulloides, Pande et al. (2003) have reconstructed the monsoon winds for the past ~ 4500 years. Low abundance of the plankton indicates weak summer monsoon winds. Description of environment from the ancient Indian text is also provided (Reproduced from Pandey et al., 2003).

Thus, changes in hydrological and climatic conditions can be inferred from the radiometric dates and characteristics of the deposits.

Many workers have investigated riverine or fluvial deposits of several Indian rivers, the Ganga, Son, Sabarmati, Mahi, Luni, Narmada, Godavari, Krishna, Kaveri and the Pennar. These studies indicate that there were distinct periods of erosion and incision (*degradation*) and sediment deposition (*aggradation*) associated with changes in the monsoon conditions and sediment supply. Periods of aggradations are linked to periods of weaker monsoon and higher sediment supply, and the periods of stronger monsoons are associated with erosion and incision and reduced sediment supply. Figure 12 provides a glimpse of a typical record laid down by a river. Occasionally, sea level has a role by way of a base level shift and hence the gradient that is available for the river flow. A change in the gradient changes the sedimentation style and this is used in reconstruction of the past.

A spatial variability in response of rivers to changes in the monsoon strength is also documented. The following major conclusions emerge from the study of fluvial records in India (Kale, 2007, Fig. 13).

1. During the Last Glacial Maximum at ca 21, 500 years ago, river discharges to the Bay of Bengal and the Arabian Sea were markedly reduced. This is consistent with the evidence from marine sediments of weaker southwest monsoon. By and large, this was a period of sediment aggradations in the Indian rivers and disruption of drainage systems in western India. In the Thar Desert, the drainage was seriously affected and the fluvial processes were largely dormant because of increased aridity.
2. Abrupt intensification of the monsoon around 15,000 - 13,000 yrs BP had a significant impact on the drainage systems of the Indian subcontinent. This period was marked by an abrupt and a large increase in the wet monsoon flows.
3. The early Holocene humid phase (9,000-6,000 cal yrs BP) or monsoon optimum was characterized by revival of fluvial activity in the Indian subcontinent and increased weathering and fluvial erosion in many parts. The Bay of Bengal experienced high sediment influx from 11000 -7000 cal. yrs BP.

Fig. 12: A geological section exposed at Rayka on the banks of Mahi River. The panel on the right shows the ages and the nature of the deposit which informs on the depositional environment and hence the climate/monsoon. Kindly provided by Dr. N Juyal

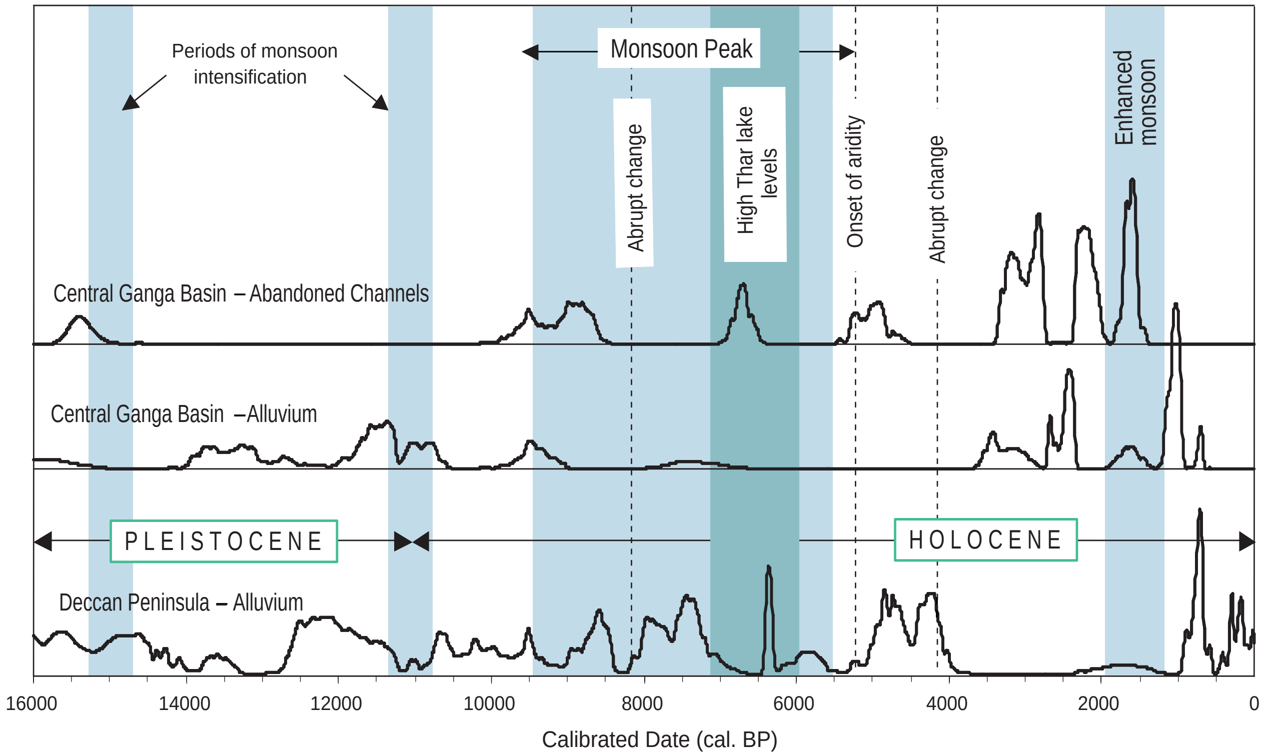

Fig. 13: Summary diagram showing identified alleviation phases in the central Ganga basin and the Deccan Peninsula during the last ~15cal kyrs BP. The three curves represent the summed probability distribution plots (After Kale, 2007 and references there in).

4. Unusually high sediment output and water discharge under conditions of an intensified early Holocene monsoon in the Himalayan Rivers is indicated by deltaic deposits of the Ganga–Brahmaputra Rivers.
5. The sediment discharge from the Ganga–Brahmaputra Rivers dropped significantly after about 7,000 cal yrs BP indicating weaker monsoon conditions.
6. The late Holocene was marked by multiple short-term phases of aggradations and degradation, which were not spatially synchronous.
7. The rivers in southern India do not exhibit any evidence of increased flooding during the recent four centuries as suggested by the ocean core records. This implies that the increase in monsoon winds may not necessarily imply spatially uniform increase in rainfall.

An interesting comparison was recently attempted on the sediments of river Pennar. This river floods during the peak of monsoon and a general correlation of its flooding with periods of enhanced monsoon is established. The flood record using sediment deposited thorough overbank overflows was established using field observation and this besides other observations indicated that during the period 135 years to 80 years, eight flood events occurred and for the past 80 years only 3 major floods occurred.

This evidence is in accordance with the instrumental data of this period but does not agree with the suggested increase in monsoon winds intensity during the past few centuries due to global warming. This suggests that the monsoon winds inferred from marine records may not provide a meaningful measure of rainfall on land (Fig. 14 and 15).

Paleoflood Records

Terrestrial records of extreme climatic events include 'slackwater flood deposits (SWD)'. Stratigraphical, sedimentological and chronological studies of the slackwater deposits provide reasonably accurate information about their timing and magnitude of past or ancient floods. Normally, a river receives water from its tributaries. However, during large floods, the water flows into tributaries to a point decided by the elevation of the flood waters such that at the terminal point the velocity of water is near zero (slack) and the sediments brought in suspension by the flood are then deposited by Stokes settling law, i.e. sands are deposited first followed by silt and then clays. Clays being cohesive, preserve the records and in the field a succession of sand, silt clays, and their elevation with river channel geometry enables reconstruction of the magnitude and the frequency of the floods. An analysis of modern flood and rainfall data informs on the modern day conditions of floods and the same are extended the past to deduce the paleoflood records. Figure 16 provide a typical field exposure of slack water deposits of river Kaveri.

Investigations of paleoflood records in some of the central, western and southern Indian rivers, namely, Narmada, Tapi, Godavari, Krishna, Pennar, Kaveri and Luni have indicated significant changes in the frequency and magnitude of large floods during the last two thousand years

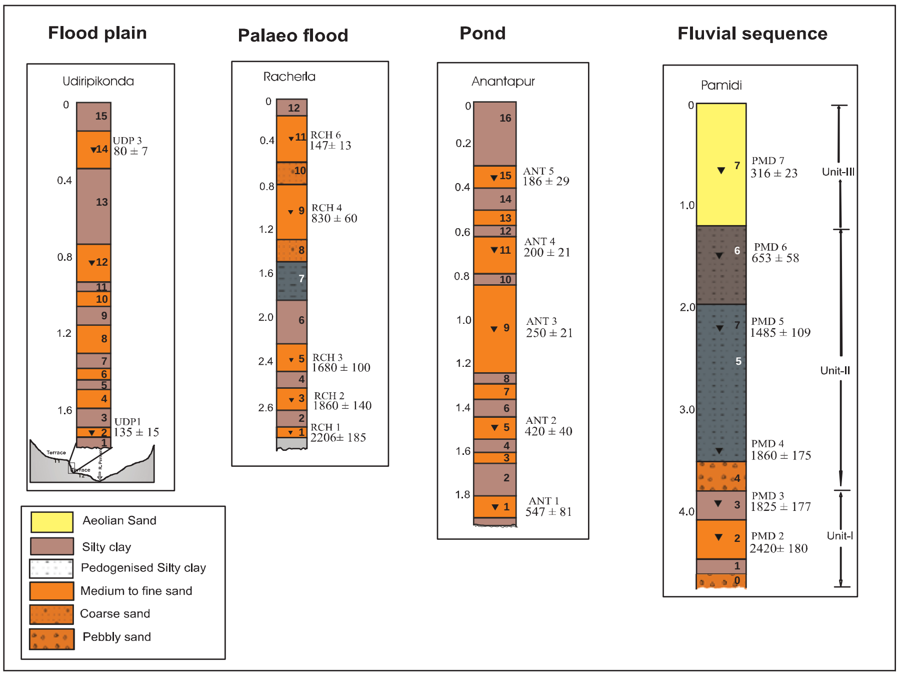

Fig. 14: Geological record of floods in River Pennar dated using luminescence. Modified after Thomas et al., 2007.

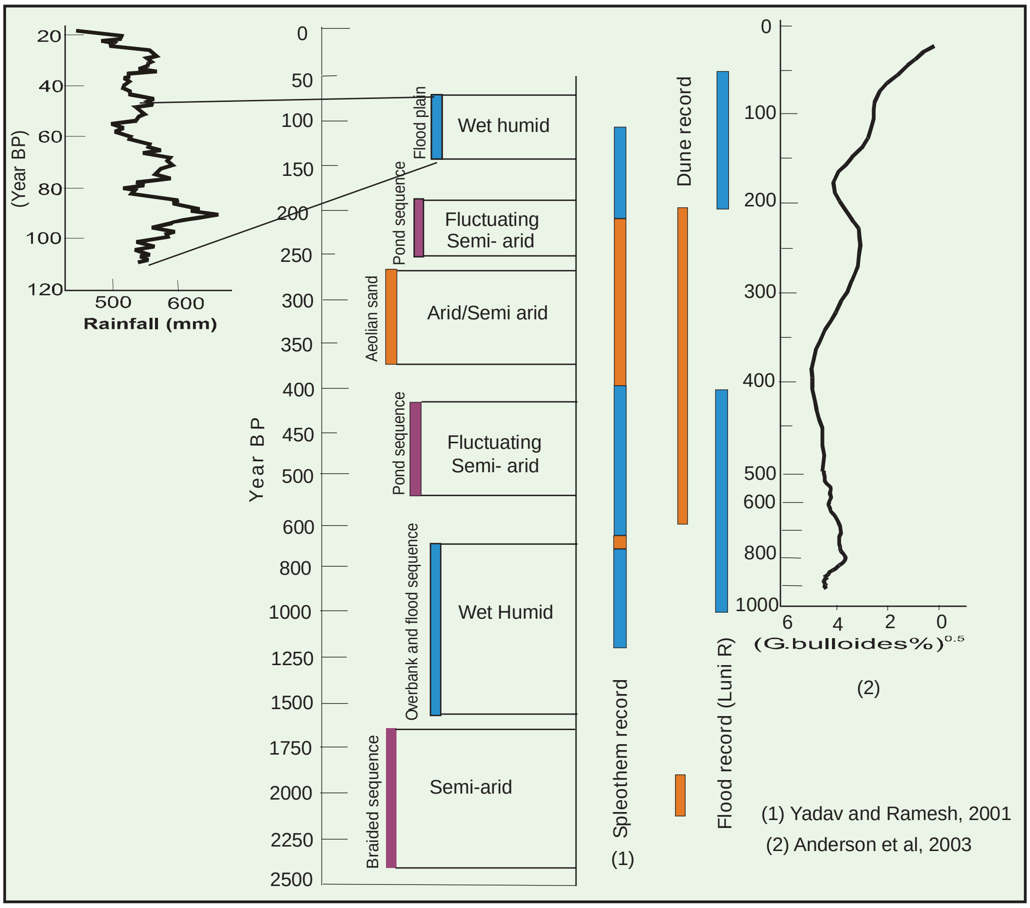

Fig. 15: A summary of the recent record of climate reconstruction using instrumental, River Pennar, speleothems, dunes, River Luni and ocean core record from Arabian sea. It is noteworthy that both the instrument records and Pennar record do not show an increase in monsoon rainfall. However the marine records suggest a steady increase. Kindly prepared by Dr. N Juyal.

(Fig. 17). In general, the records reveal a noteworthy absence of large-magnitude floods during the late Medieval Warm period and the Little Ice Age (ca. 700-400 yrs BP). (Kale and Baker, 2006). Historical and other proxy records indicate that this was also the period of increased frequency of droughts in South Asia. There is also an evidence of clustering of low-frequency, extreme floods between 400 and 1000 AD and into the most recent period (post-1950). In addition, a catastrophic flood on the Tapi River at the beginning of LIA (ca. 300-400 yrs BP) and a highly erosive flood on the Narmada River at the commencement of the Christian Era (ca. 2000 yrs), have also been inferred from the paleoflood records. On the basis of modern analogues, it appears that the century-scale variations in the flood magnitude and frequency are intimately linked to long-term fluctuations in the monsoon rainfall.

Fig. 16: Slack water deposits of River Kaveri upstream of Hogenakal Falls (Provided by Dr V.S. Kale).

Lacustrine Sediments

On account of the potential of lake sediments for paleoclimatic reconstructions, many studies of environmental change in India are based on lacustrine deposits in the Himalay and western India (Bhattacharyya, 1989, Kusumgar *et al*., 1992, Prasad *et al*., 1997, Chauhan *et al*., 2000, Enzel, *et al*., 1999, Sinha *et al*., 2006). Some studies of lake deposits from the Deccan Peninsula have also been taken up (Shankar *et al*., 2006). Reconstruction of past climate from lake records used grain size of lake sediments, the organic matter and their carbon and oxygen isotopic ratios, magnetic susceptibility, mineralogical and geochemical changes that were related to local pH. Thus, for example, a simple change in the lake sedimentology from being clays/silt only to clay and silt with gypsum and gypsum only was used to infer paleo-lake levels.

A large body of work has been done on the lakes of Thar, where not only the pollens grains were analyzed, but their transfer function with rainfall was deduced and applied to quantitative reconstruction of past rainfall. During the post-LGM period, the lakes in the Thar Desert underwent

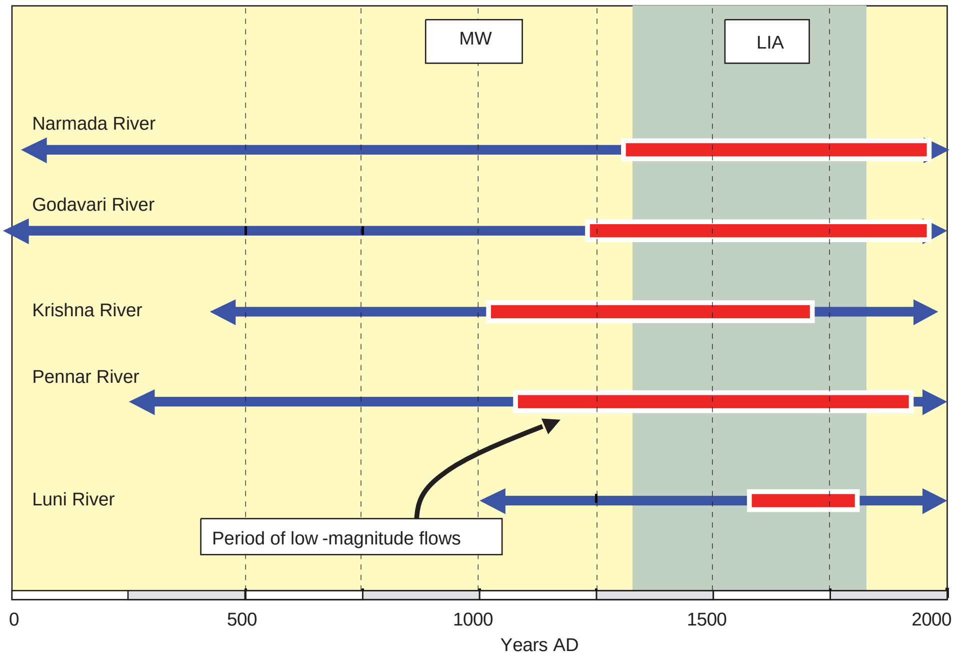

Fig. 17: Diagram showing the period of low-magnitude floods during the last 2 kyrs. Red bars represent the period of less frequent large floods. The blue thin lines with arrows represent the length of the paleoflood record on each river. The shaded area is the period of Little Ice Age (LIA), between 1300 and 1850 AD. MW = Medieval Warming (Provided by Dr V.S. Kale).

considerable hydrological changes nearly completing a full cycle of freshwater conditions to desiccation and finally the present saline conditions (Fig. 18). Numerous studies of the lakes indicate (Prasad and Enzel, 2006):

1. Relatively higher lake levels and near fresh water conditions were reached around 7,200 and 6,000 cal yrs BP.
2. The desiccation of lakes in northwest India began after 5,300 yrs BP.
3. The late Holocene was characterized by multiple wet events of shorter duration and smaller magnitude.

A synthesis of paleohydrological studies of the saline playas indicates that the P-E (Precipitation - Evaporation) balance ensured a gradient in the lake hydrology from the eastern to the western Thar Desert. Thus, the lacustrine (perennial) phase of eastern playas existed for 8,000 yrs BP. The north-western playas had fresh water condition only for 2500 yrs BP, whereas the playas in the extreme western desert remained perennially saline. Since the Holocene monsoon optimum, the western playas became ephemeral and saline at least 1000 years earlier than the north-western and 3000 yrs earlier than the eastern playas.

Studies of three lakes associated with abandoned rivers channels in the Ganga Plains, namely Basah Jheel, Sanai Tal and Misa Tal indicate that conditions favoring channel abandonment were initiated during early Holocene monsoon optimum. The lake deposits of the Sanai Tal have provided the first dated record of human inhabitation in the Ganga Plains.

Studies on the relic lakes of the Central Himalay region that were formed due to natural damming of tributary glaciers have provided rich archive of climate change (i.e. monsoon) for the period 20-11kyrs. These indicate that the monsoon has low frequency high amplitude oscillation during the period 20-13ka which change due to high frequency low amplitude fluctuation during 13-11 ka. Later records are not available as the lakes here breached and other sites have not yet been examined (Fig. 19, 20).

Peat Deposits

Paleoclimate records are available from three peat deposits (Dokriani and Dayara Peats in Bhagirathi Valley of the Garhwal Himalay and the Dhakuri Peat deposit in Pinder Valley of the Kumaon Himalay) and from southern India (Nilgiri peatbogs, Sukumar *et al.*, 1993).

Centennial-scale climate records (pollen, diatoms, phytoliths, organic matter and magnetic susceptibility) from the Dhakuri peat deposit (Phadtare and Pant, 2005, 2006) indicate rapid weakening of the southwest monsoon at ca. 3200 and 2000 cal yrs BP. The monsoon also influenced peat deposits of the Tibetan Plateau. The peat record indicates depleted monsoon around 3,200 cal yrs. BP (Hong *et al.*, 2003). Except for a century of dry phase during 740 – 640 cal yrs BP (i.e. ~1260 – 1360 cal yrs AD), the climate progressively improved until present, with warmer temperatures during 1600 – 740 cal yrs BP (~400 – 1260 cal yrs AD), 640 – 460 cal yrs BP (~1360 – 1540 cal yrs AD), and 270 -57 cal yrs BP (~1730 – 1940 cal yrs AD) intervals, and relatively cool and dry conditions during the intermittent periods. The carbon isotopic studies from a low resolution peat record from south India spans a longer time scale and during the past 20 kyrs, it shows dry periods around 20, 5-3 and 1 kyrs BP and wetter periods around 10 kyrs, with evidence of progressive drying up during the past 10 kyrs.

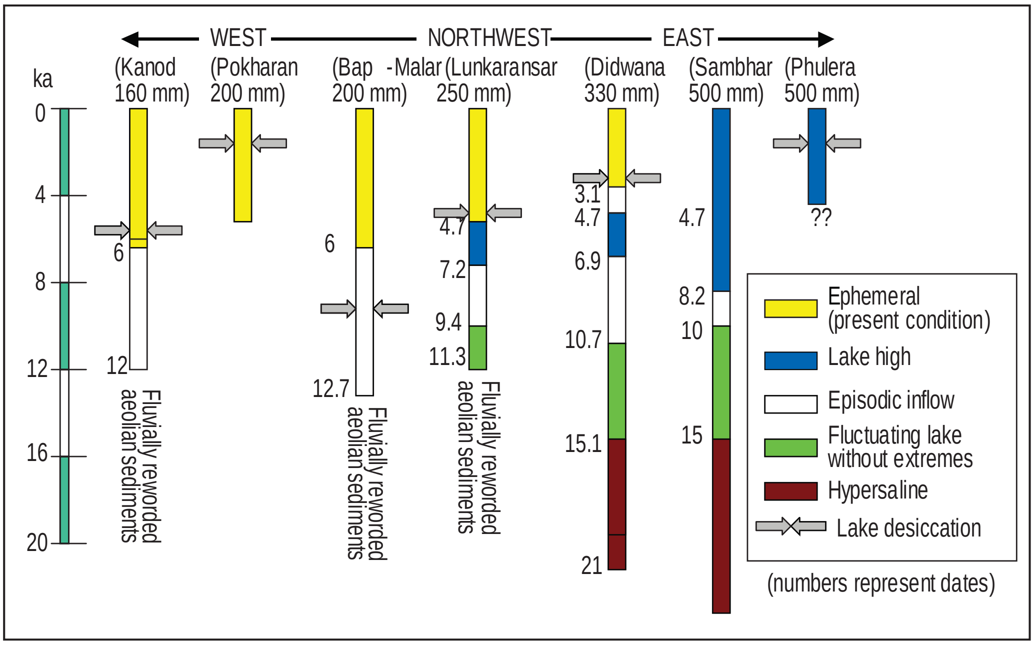

Fig. 18: Diagram comparing the responses of seven Thar playas/lakes during the last 20 ka. Notice that in a spatial extant of 250km the lakes have desiccated at different times. Prepared with the kind help of Dr. PD Roy, Mexico.

Fig. 19: Field photograph of a relict lake sediment sequence in central Himalay at an elevation of 3500 m. The picture on the right indicates the physical appearance of annually deposited layers of sediments (called as Varve bundle). This is a close up of the lake deposit identified as rythmite (repeated pattern of deposition) containing several layers of varves on mm size. A varve comprises a lighter summer and a darker winter layer and these together represent a year. Typical thickness of the rythmite is a few cm. Kindly provided by Dr. Navin Juyal.

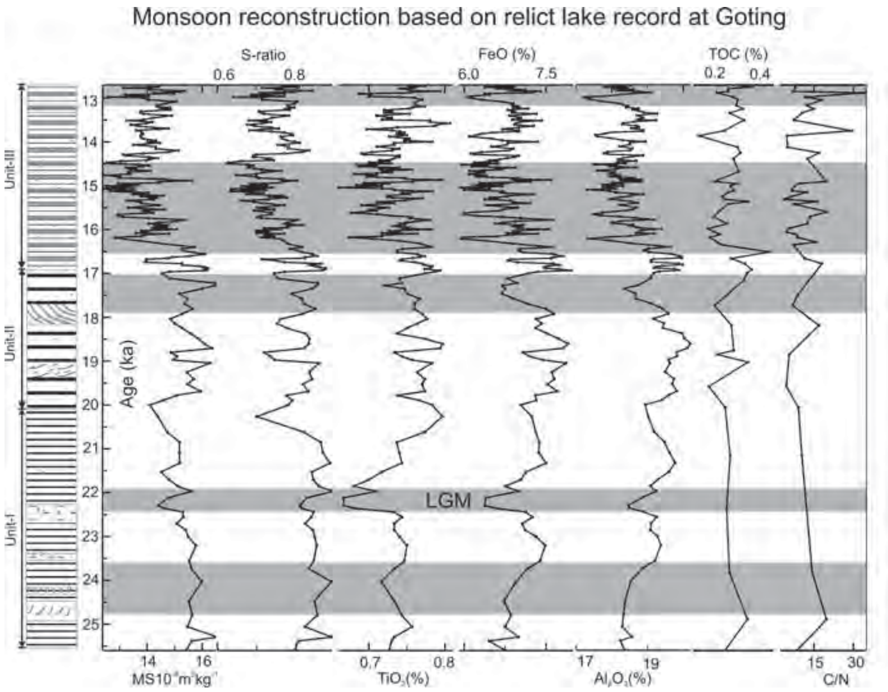

Fig. 20: Reconstruction of the monsoon using a variety of proxies. These proxies essentially reflect the changes in the weathering intensity in the catchment area a surrogate for monsoon variability. Adopted from Juyal et al. 2004.

Studies of peat bog from Nilgiri Hills indicate that the period between 30 and 18 kyrs BP was characterised by relatively drier conditions and during 18 to 10 kyrs BP more humid conditions prevailed. The Holocene was, by and large, characterised by alternating periods of wet and dry climates.

Tree Rings

As stated earlier, the study of tree rings for determining past climatic conditions (temperature and precipitation) is known as "dendroclimatology". Certain species of trees (pine and teak, for instance) show distinct growth ring each year. The growth rings or tree rings are wider when temperature and moisture conditions are favorable for growth. Using tree ring widths, density and isotopic composition, scientists have been able to reconstruct local climate conditions from several decades to thousands of years. The width of a ring depends on environmental factors that include ambient temperature and rainfall. In paleoclimate reconstruction using tree rings, firstly a correlation of the ring widths with various parameters from instrumental record are examined. These parameters are then used to verify the correlation for another time period. Once this is done and correlation established, then the ring widths of other periods are used for paleo-reconstruction. Figure 21 (a,b,c) provides a sample of temperature reconstruction using tree rings, carried out at the Birbal Sahni Institute of Paleobotany (BSIP). Typically tree ring width data can explain up to 40% of the variance of temperature and rainfall signal and only an annual mean of the temperature or rainfall is recorded.

From the late seventies (Pant, 1979), several precisely dated tree-ring chronologies from western, central and eastern Himalay have been developed for climatic studies. The climate reconstructions so far are for mean temperature of the pre-monsoon season (Borgaonkar *et al*., 1996, Hughes, 1992, Yadav *et al*., 1997, 1999, Yadav and Park, 2000, Yadav and Singh, 2002, Yadav *et al*. 2004). Further, irrespective of the length of record, the climatic reconstructions here consistently show a periodicity on decadal to inter-decadal scale. The longest

Fig 21a: Juniperus polycarpos (Himalayan pencil juniper), the oldest found in India and annual rings (left). Kindly provided by Dr. RR Yadav.

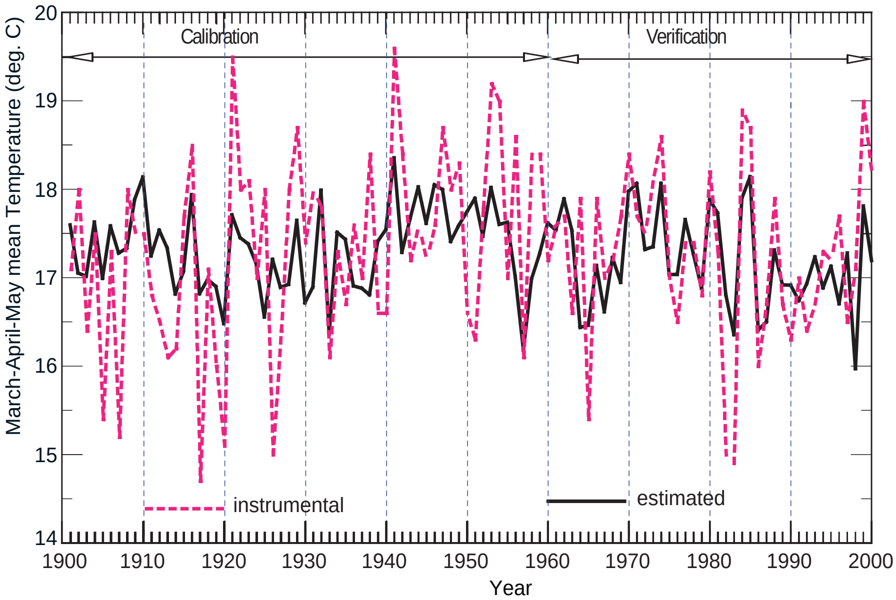

Fig. 21b: Calibration of tree-ring data with March-April-May mean temperature (1901AD-1959 AD) and verification of estimated values against the instrumental data (1960AD-2000 AD). Kindly provided by Dr. RR Yadav, BSIP, Lucknow.

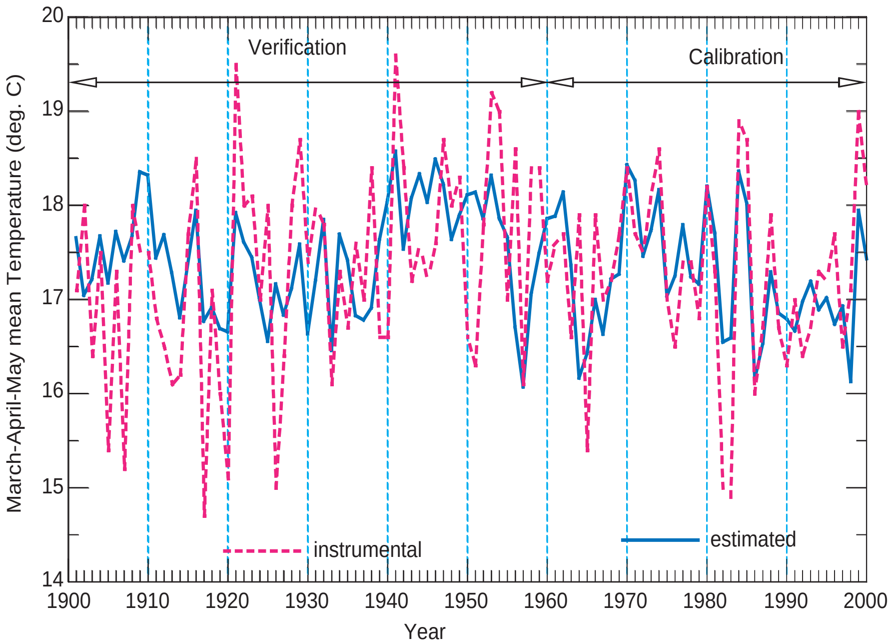

Fig. 21c: Calibration of tree-ring data with March-April-May mean temperature (1960AD-2000AD) and verification of estimated values against the instrumental data (1901-1959 AD). Notice that different periods have been used for calibration and verification, but both lead to identical results suggesting robustness of the analyses. Kindly provided by Dr. RR Yadav, BSIP, Lucknow.

mean pre-monsoon temperature reconstruction is from network sites in western Himalay, each extending to 500 years or more (Fig. 22 Yadav *et al.*, 2004). This mean pre-monsoon temperature reconstruction (1226-2000 AD) shows cool episodes around 1573-1622, 1731-1780, and 1817-1846 and 1560-1610 AD and coincides with the extension of glaciers in the Himalay. The 18th century was cool in the western Himalay. The 18th and early 19th century cooling episodes in western Himalay are contemporaneous with cooling in Nepal, Tibet, Central Asia and Karakoram (Briffa *et al.*, 2001, Cook *et al.*, 2003).

The pre-monsoon temperature reconstruction does not show warming towards the late 20th century. This is similar to other tree ring based temperature reconstructions from the Asian region. Analyses of century long meteorological data of stations from the western Himalay show steady warming in maximum temperature throughout the 20th century. However, contrary to this, the minimum temperature shows warming trend up to 1950's and decreases thereafter. Reduction in minimum temperatures since 1960's outbalances the warming trend in maximum temperatures and leads to slight cooling trend in mean temperatures after the 1950's. As the tree rings respond to mean temperature only, the maximum temperature has not been reconstructed. This is to be contrasted with the recession of glaciers and extension of treeline to upper elevations (Dubey *et al.*, 2003), which respond to both the maximum temperature and precipitation. Some efforts in the use of isotopes of carbon and oxygen in cellulose have also been made.

Reconstructions for the paleo-precipitation for the Himalayan region are few. Using a network of tree-ring data from 15 moisture-stressed, homogeneous sites in the region, Singh and Yadav (2005) reconstructed pre-monsoon precipitation for the period 1731-1986 AD. The reconstruction showed strong decadal to inter-decadal scale variability in precipitation. This reconstruction revealed lowest and highest 20-year mean precipitation during the 20th century. An increasing mean pre-monsoon precipitation trend since 1970s coincides with a decrease in summer monsoon rainfall over the Indian region. Winter and pre-monsoon precipitation over the Himalayan region have inverse relationship with subsequent summer monsoon rainfall over India. This implies that such long-term information on pre-monsoon precipitation could be useful in understanding the intricacies of monsoon system *vis-à-vis* predictions.

The dendroclimatic reconstruction from the eastern Himalaya extending up to 1507 AD has been made using composite tree ring chronologies of *Abies densa* from two sites, T- Gompa (Arunachal Pradesh) and Yumthang (Sikkim). Reconstructed temperature series reveal that,

1. No significant change in temperature during the past five centuries.
2. Decadal scale fluctuations. Thus, 1760s, 1780s, 1800s, 1830s, 1850s and 1890s are recorded as cool decades with the minimum occurring in 1801-1810 (-0.31°C). Period 1978-1987 (+0.25°C) was the warmest one (Bhattacharyya and Chaudhary, 2003).
3. No long-term cooling corresponding to the Little Ice Age. Although, evidence of a reduction in late-summer temperature variability from the late 1700s to 1900 is seen in the present study, it does not show significant negative anomalies over the longer duration temperature variability.

Speleothems and Calc Tufas

Spelothems and calc tufas are secondary mineral deposits (mostly calcium carbonates) and are deposited through physical chemical or biological precipitation from lime and dolomite rich waters in caves. Spelothems grow annually and have a banded structure (Fig. 23).

Isotope composition of stalagmites has been used as sensitive indicator of monsoon variation. Fleitmann, *et al.* (2003) studied the speleothem record of the Qunf cave from Southern Oman. The record shows three distinct features.

1. A rapid increase in monsoon precipitation between 10,300 and 9,800 yrs BP.

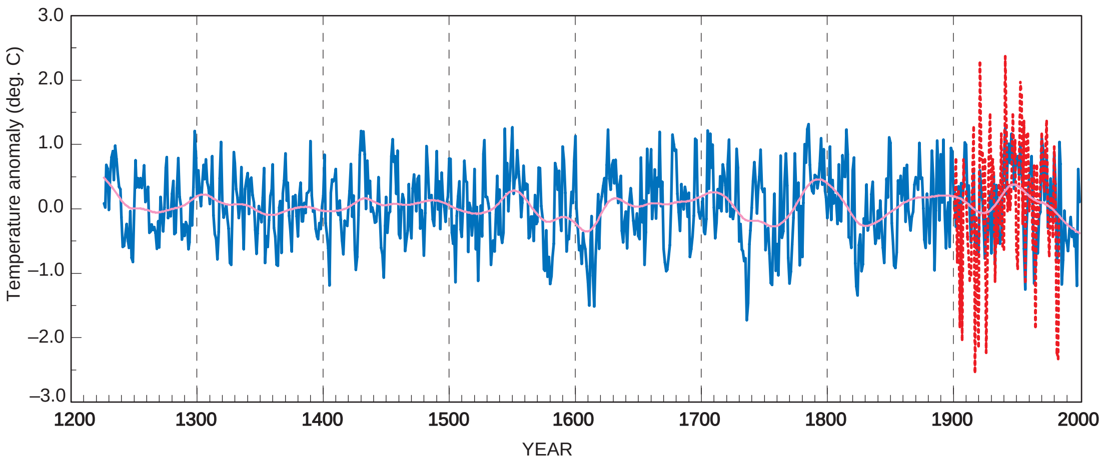

Fig. 22: March-April-May mean temperature reconstruction shown as anomaly relative to 1961-1990 AD mean. Smooth line (in red) represents the filtered version of reconstruction to emphasize variations in time scale of 50 years and above. Dotted line represents the instrumental data superimposed over the reconstruction. Notice the decline in the recent years. Kindly provided by Dr. RR Yadav, BSIP.

Fig. 23: Spelothems from caves in Kurnool, Andhra Pradesh. A slice from this showing annually laminated bands in a sample from Aklagavi cave, Uttar Kannda district of Karnataka. Kindly provided by Dr. MG Yadava, PRL.

2. High monsoon precipitation from 9,800 to 5,500 yrs BP.
3. Decrease in monsoon precipitation after 7,000 yrs BP.

Reconstruction of the monsoon precipitation from $\delta^{18}O$ of a stalactite from two caves in eastern India, namely Gupteswar cave in Orissa and Dandak cave in Chhattisgarh was attempted by Yadava and Ramesh (2005). The records indicate an arid phase before ~1200 yrs BP, a 14 year arid event around 2000 yrs BP and a high rainfall event around 600 yrs BP. Another study of the stalagmite oxygen isotope record from Timta Cave in western Himalay (Sinha *et al.*, 2005) indicates variations in the monsoon precipitation from 15,200 to 11,700 cal yrs BP). A speleothem mineralogical record from a dolomitic cave in Pokhara Valley (central Nepal) documents the summer monsoon variability over the past 2,300 years (Denniston *et al*, 2000). The aragonite annual layers formed between 2,300 and 1,500 yrs BP indicate reduced monsoon precipitation, whereas alternating calcite/ aragonite laminae deposited after 1500 yrs BP document increased monsoon conditions. Optically clear calcite layers deposited from 450 to 360 yrs BP (1550 to 1640 AD) indicate less evaporative (i.e. cooler) environment possibly related to climatic change associated with the onset of LIA. Wavelet analysis of some of the spelothem data has indicated that the reconstructed monsoon intensity has a 22 year cycle. This is similar to the cycles of droughts seen in the monsoons, (Fig. 24).

Calc tufas are calcium carbonated deposits at springs and waterfalls. In the Deccan Trap region, evidence of enhanced precipitation, discharge and groundwater levels is provided by the building of waterfall tufas between 9.8 and 8.1 ka (U/ Th) in the rain shadow area of the Western Ghat (Pawar *et al.*, 1988).

Aeolian Sands, Dunes and Dust (loess)

The term Desert comes from the word "*tesert* or deserted" and this by definition implies that the region was more habitable – i.e. had undergone climatic change. The Thar Desert of India is an extension of the Arabian Desert. Although the arid region is under the domain of the Arabian Sea branch of the southwest monsoon, the rainfall is remarkably low because of temperature inversion in the lower troposphere (Das, 1991). Due this atmospheric condition, the moisture laden monsoon winds are not able to rise and reach the point of saturation and contribute to rainfall. Thus, the geographical location of the Thar Desert implies that minor perturbations in this pattern influence the earth surface processes in the region, on an amplified scale and consequently has been a focus of major studies. The current dune building activity is

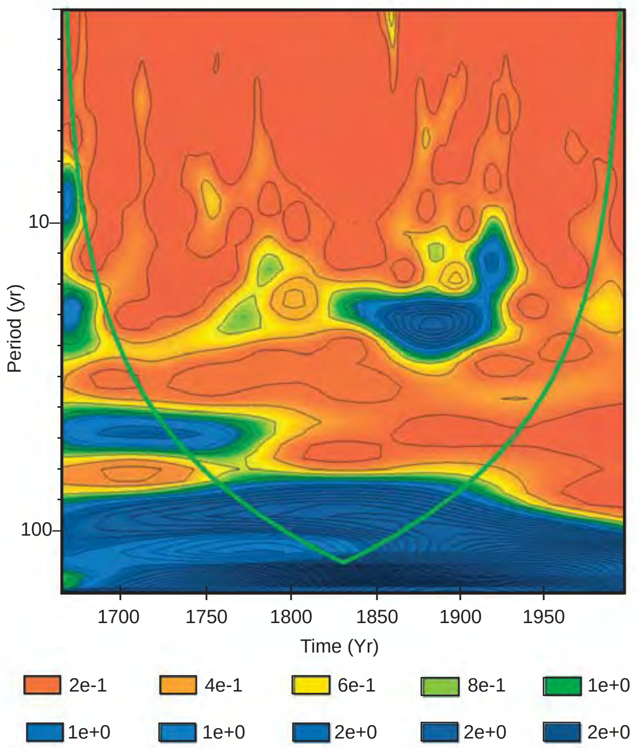

Fig. 24: Time series Wavelet analysis of isotopic data on annually laminated speleothem from Akalgavi cave, that indicates a 22 year periodicity (blue island in the centre of the figure). Kindly provided by Dr. MG Yadava.

limited to regions with annual rainfall less than 250 mm. Therefore, the presence of fossil dunes in areas of rainfall >250 mm, itself implies a climate change. Based on this an eastward shift of dune forming climate of 300 km has been suggested.

Contrary to a general notion of desert being areas of moving sands, the desert sand dunes also accrete under specific environmental condition and their shape is determined by the wind vector and its consistency. The climatic controls of dune building arises from the manner a dune gets constructed. The parameters needed are, the sand supply, the wind vector and the vegetation. Only when these are optimum, dune accretion occurs. Thus, a record of dune comprises sand and weathered sand/soil horizons and in the Thar desert, over 20 soil horizons in a dune dated over 150 ka have been seen. Discovery of Middle and Lower Paleolithic tools in this dune attest to their long antiquity (Fig. 25).

An important result from the Thar Desert has been that the dune building peaked at around 13,000 yrs and not at the peak of Ice Age at 21,500 yrs (Singhvi and Kar, 2004). Explanation of this fact, using the modern wind and rainfall data, and sand movement condition suggest that the winds for sand movement precede the monsoon system and are controlled by the same mechanism. The sand dynamism and monsoon are, therefore, connected. Other proxies, mainly marine, suggest that during the Ice Age the monsoon was weak and, hence, the winds were also weak such that even with the sand supply, dunes could not move sands and stabilize them on account of aridity. With the onset of monsoon, the winds picked up moving the sands. At this time the vegetation was also sufficient to provide trapping site for sands to build dunes. However with the intensification of monsoon the winds remained strong enough but the vegetation cover also increased leading to reduce sediment supply. This phase facilitated soil formation. Thus, only a narrow window of opportunity was available to construct a dune and this was during a transition time when the monsoon was being established. Should this be so, then the dunes in Thar have the potential to provide data on monsoon during the past 200 ka, on the premise that dune accretion on the regional scale occurs during transitional climate.

During the Holocene also, phases of dune activity are seen and these correlate well with the lake records of monsoon change. Major phases of aeolian (wind) activity after the Holocene climatic optimum were between 5 and 3.5 ka, and 2 and 0.8 ka (0.6 ka in the western part). Interestingly, the Harappan and pre-Harappan civilizations in the northern part of the desert flourished during a waning phase of the southwest monsoon, when rainfall events were more aberrant and aeolian activities high. No wonder they depended more on winter crops and practiced water harvesting. The records suggest that whenever the lakes dried, the dunes became active and vice versa. A 1500 year cycle in this (and hence

Fig. 25: A section cut open in a dune in the Thar Desert. This dune at Didwana has provided a 200,000 year record of human occupation and environmental change. This dune record indicates that the dune activity (age of desert is 200,000 year and hence is of geological origin as against being of human origin. This record has also provided new insight in the manner the sediment records are to be interpreted vis a vis climate. Kindly provided by Dr. H Achuythan, Chennai.

monsoon) has been reported. In the more recent times, a lull in aeolian activity between 0.6 and 0.3 ka reflects a reduction in monsoon and winds. Also it was seen that the dune stabilization began about 200 years earlier in the east compared to the western margin suggesting that it takes about 200 years for the monsoon conditions appropriate for sand accretion to move eastwards. The dunal record of southern margin of Thar suggests progressively northward trend of dune stabilization over the past 10,000 years. This relates to largely a sand supply (vegetation) shift through time and suggest progressive wetting of the region over the past 10,000 years (Fig. 26). In summary, the dune records provide a key potential to unravel the monsoon for a much longer time scale. The specificity of dune accretion to winds associated with the monsoon suggests it's potential for reconstruction of post monsoon. The transition to the peak of subsequent wet phase, the Holocene climatic optimum was also marked by increased aeolian activities.

Another important archive is aeolian dust. This is generally produced by rock grinding by glaciers or is supplied by deserts. The transport and deposition is controlled by meteorological parameters. Such dust is normally deposited as a blanket with characteristics sedimentation features. Loess deposits in Kashmir valley have been extensively studied but most of these deposits belong to time period >20 ka. A more recent study on loess from central Himalay has indicated that the region experienced a drier and dustier climate during 20 - >15 kyrs, 12 - > 9 kyrs and 4 to > 1 kyrs suggesting these to be phases of weaker SW monsoon. Evidence of stronger monsoon at 16 kyrs, 12 kyrs and during 9 - > 4 kyrs is seen via soil formation on the loess deposits. It is perhaps apposite here to mention that in China extensive deposits of loess spanning past several million years exists and have provided a detailed chronicle of East Asian monsoon.

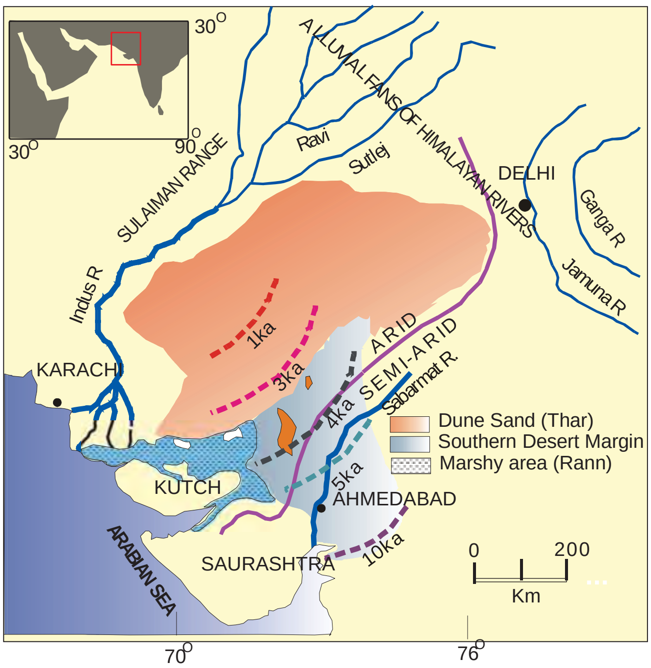

Fig. 26: Changes in spatial accretion domains of sands through time. Notice movement of accretion boundary, northwest wards. Presently the desert is in a contracted scale. Kindly prepared by Dr. N Juyal, PRL.

Groundwater Temperatures and Bore-hole Temperature Studies

Radiocarbon dating and isotopic studies on ground waters have been shown to reflect past temperatures and a demonstration of this concept was made on south Indian ground waters. Some studies in Tamil Nadu (Sukhija, *et al.* 1998) and Gujarat show that the ground waters are a few tens of thousands of years old and their isotopic signatures carry imprints of past temperatures. Recently effort has been made to analyze the changes in subsurface temperature with depth to deduce past temperatures. This approach used the fact that normally the sub-surface temperature below 15-20 m is devoid of diurnal changes and is only affected on decadal and century scale surface temperature variation. A measurement of the actual measurement vs. the expected temperature profiles provides a good estimate of changes in the air temperature during the past (Fig. 27).

4. PRACTICAL APPLICATIONS OF PALEOCLIMATIC STUDIES

Besides elucidating the nature of natural variability of climates, paleoclimatic studies inform on several aspects of societal importance. For example, information on landform stability is an important aspect. These studies inform on the durations of and conditions under which landforms get stabilized. These are important for the development of realistic land use planning. Thus, for example, if it can be established that a landscape surface took a few hundred years to stabilize, it will be prudent to provide a vegetation cover that will be effective over long time scales. On the other hand, if it can be established that the surface can be activated fairly easily, the immediate stabilization using rapidly growing vegetation

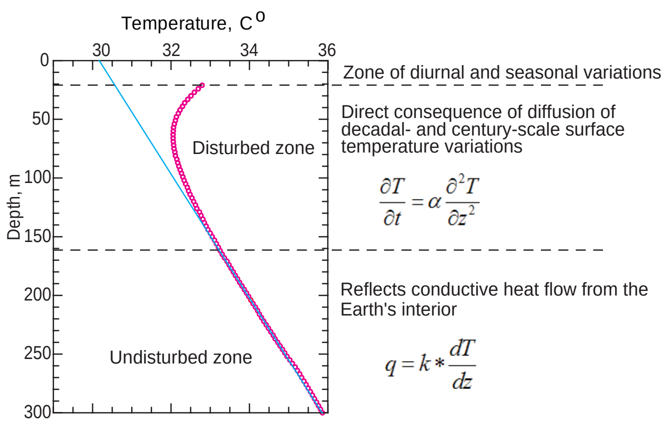

Fig. 27: A typical borehole temperature-depth profile showing (i) the zone affected by diurnal and seasonal variations of surface temperature, (ii) the zone affected by decadal- and century-scale surface temperature variations, and (iii) the zone unaffected by transient perturbations, reflecting the steady-state heat flow from the interior of the Earth by conduction. [T: temperature, t: time, z: depth, α: thermal diffusivity, q: heat flow, k: thermal conductivity]. The dotted line provides the observed profile. Kindly provided by Sukanta Roy, NGRI Hyderabad.

cover is desirable. In the Thar Desert, for example, dune surfaces have been stable for the past few hundred years. It would, therefore, be imprudent to destabilize these surfaces by ploughing. The studies on Thar also inform that in areas of overgrazing that reduce the vegetation cover, the dune migration rates get accelerated by several folds (Fig. 28).

In the Himalay, a recent study on sediment fluxes through time suggested that the contribution from lower Himalay occasionally gets accentuated by natural processes of lake formation and breaching over century to millennial time scales. This is contrary to the views so far, that this occurred only recently due to deforestation in lower Himalay by human activity. The implications are that besides human activity, natural forces also play an important role in contributing to copious sediment fluxes. This study incidentally was initiated by debate that ensued the catastrophic 1970 Alaknanda floods. An important message that the paleorecords have provided is that sediments, wherever they are, exist due to a special combination of local geology and climate and reflect a narrow window of opportunity in space and time. Any tempering with them should be done with due care of processes involved (Fig. 29 and Table 3).

Similarly, paleoflood studies provide a more robust account of the extreme floods and their recurrence interval. These are important inputs for planning of infrastructure in the region. Identification of extreme events and their periodicity is important for any such planning and it is likely that the short instrumental records did not capture an extreme flood event that is likely to occur once in two centuries. Isotopic studies on the sediment transported by Ganga to the Bay of Bengal show that the flux is dominated by the contribution from the Gandak and the presence of hot spots in the Himalaya contributing to sediment flux and influencing local tectonics (Krishnaswami and Singh, 2008).

The paleoclimatic proxies have indicated that warming conditions, similar to those recorded in the 1990s, have occurred in the past. Therefore, the critical issue is not the human-induced warming but the rate at which the global temperatures are rising, which are unnatural and hence present a great potential threat.

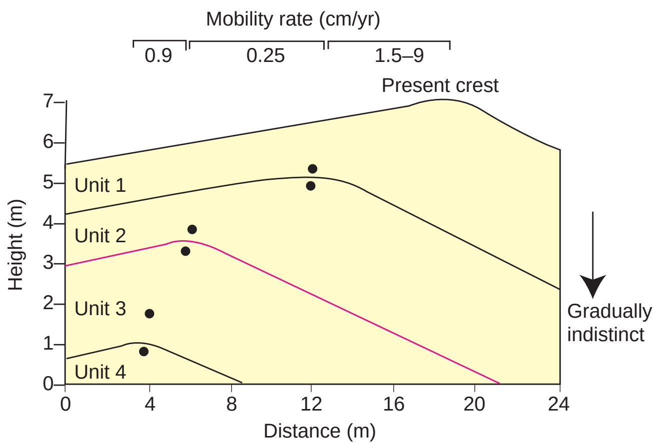

Fig. 28: Dune migration rates through the time. Notice the recent increase in the dune migration rate. Modified after Kar et al., (1998).

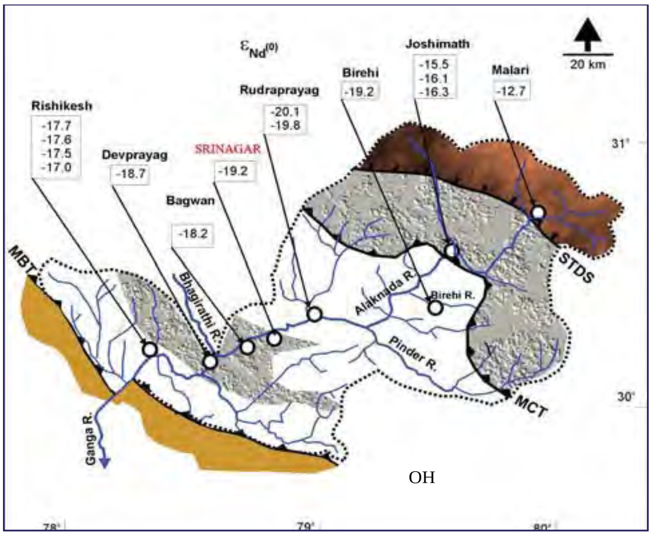

Fig. 29: Nd isotope values of sediment of Alaknanda River that were used to deduce their provenance. Here STDS abbreviates for South Tibetan Detachment System, MCT is main central thrust and MBT is main boundary thrust. Kindly prepared by Dr. Navin Juyal, PRL, Wasson et al. (2008).

Table 3: Chronology and provenance of fluvial sediments around Srinagar (Garhwal)

Age	Higher Himalay(%)	Lower Himalay(%)
Modern	64	36
1970 AD	45	55
230 ± 60 yrs BP	67	33
400 ± 40 yrs BP	86	14
800 ± 100 yrs BP	52	48
5000 ± 700 yrs BP	86	14
6300 ± 800 yrs BP	78	22

Notice that there was an increase of sediments from lower Himalay during the Alaknanda flood of 1970 as also ca. 800a ago. This implies that nature also contributes to sediments from lower Himalay besides the human activity, Wasson et al. (2008).

5. SUMMARY AND OUTLOOK

Figure 30 provides and overview of the results from various proxies.

At this stage it is reasonable to state that while a fair amount of understanding of the climatic/monsoonal changes over the Indian Subcontinent has been achieved, there is now a need for detailed high resolution studies of monsoon variation both in the spatial and temporal domains. Limitation arise due to lack of uniformity in data density, data precision, dating accuracies and interpretations. High data density and time resolution are needed to better constrain the climate models. Some of the key inferences are:

1. The instrumental and sediment records do not show significant changes in the monsoon performance during the past century, though an increase in monsoon wind strength has been reported. The cause for these needs to be resolved.
2. While Global warming signals are seen the world over, the Indian tree ring record and other records do not as yet reflect any warming effect. This implies importance of local factors in determining regional responses to global perturbations.
3. Distinct signatures of regional scale gradients in geomorphic responses are seen. Thus the dune stabilization and the lake desiccation occurred progressively in response to the same forcing. This is an important observation that indicates the need for understanding proxy response time and geomorphic thresholds in any of the land-use land-cover planning. This is a paradigm shift from what has been practiced in the past.
4. Some signals of relation of solar forcing of monsoon have been observed but the exact dependence is to be worked out. Abrupt changes are documented but not explained.

With the improvements in the technologies, there is a need to improve upon the existing data set. Thus for example, there is a need to understand the long term behavior of the spatial variability of the monsoon. This has not been even considered. Given that this will need convergence of multi-proxy data, basic work towards quantifying individual proxy transfer functions to arrive at climate state parameters is needed. Only limited to negligible work has been done towards this aspect. We need to create infrastructure to produce laboratory data, be in dating or sedimentology, soil analysis, geochemistry, isotopes or whatever in large numbers only then more robust analysis will be possible. Major initiatives with the help of the national agencies the Department of Science and Technology, the Ministry of Earth Sciences and the Council of Science and Industrial Research for a focused, mission mode national initiative are now needed if we are to provide informed inputs to national planning. Such a program can provide a quantum jump in the paleoclimate database in a time bound manner. Some of the questions that need to be addressed are:

1. Can the temperature and rainfall record of the Indian subcontinent be created on an annual time scale for the past millennium or more? What procedures should be prescribed to make these reconstructions robust and quantitative? What are the key archives and how can their robustness be established, (for example, can the tree rings or the speleothem records provide a robust reconstruction or are there issues of proxy validation).
2. What has been the spatial variability of summer monsoon rainfall in the Indian region, during major global climatic epochs such as the Medieval Warm Period, the Little Ice Age, the Younger Dryas and the Last Glacial Maximum? What was the change in the frequency of extreme rainfall and drought events during these epochs?
3. What was the nature (intensity, timing and spatial distribution) of winter monsoon compared to the summer monsoon? Can the signatures of winter and summer monsoons be decoupled? Can we trace the southern extent of the influence of Westerlies through time? What archives can we use?
4. What factors control the onset and duration of the summer monsoon? Are there vegetation proxies that can help

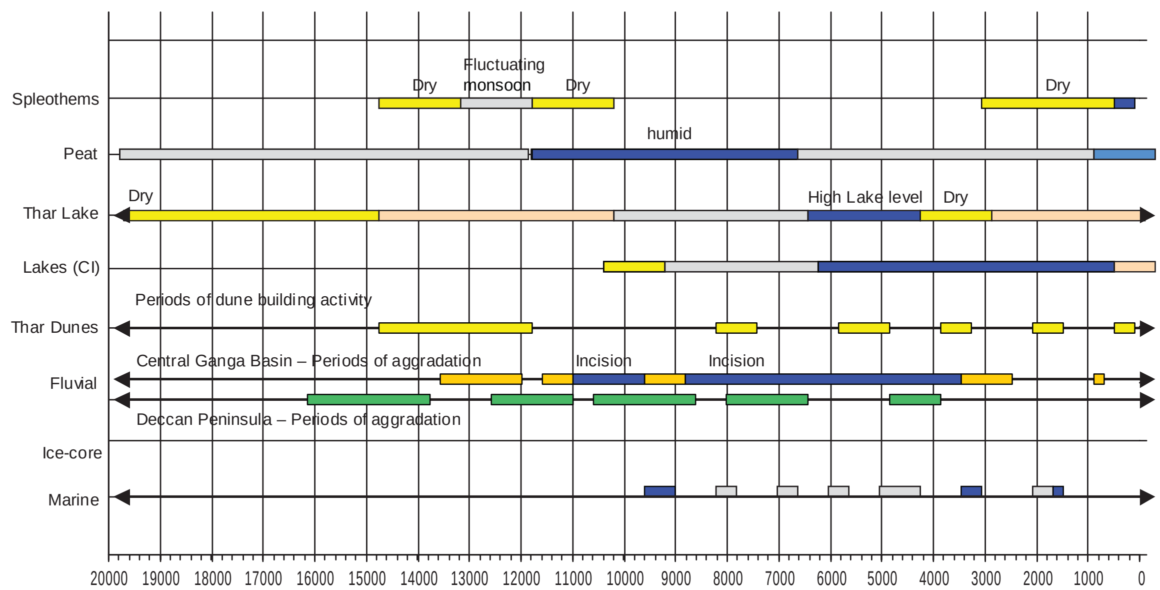

Fig. 30: A summary of the inferences from various records. The time span is based on the available chronology and the authors evaluations on optimum values.

define the duration and onset of summer monsoon season? Can other paleo-signatures help?

5. How is monsoon-induced upwelling in the Arabian Sea related to the summer monsoon rainfall over the Indian subcontinent? How well can the ages on marine sediments be constrained *vis-à-vis* realistic estimate of reservoir ages and changes in them through time? Do the Bay of Bengal paleoarchives record the same trend of summer monsoon variability as those from the Arabian Sea?
6. How has the vegetation responded to monsoon through time and how has the monsoon affected the vegetation?
7. How variable has been the summer monsoon rainfall across the Indian landmass in the recent tiles? Did the western part receive different amounts of rain compared to the eastern or northern regions and can they be understood in the light of recent models?
8. How have large and small river systems processed climate change in terms of sediment budget, sedimentation style and hydrology? What was the contemporary sediment dynamics then and what were the controlling factors?
9. How can lacustrine archives be used to reconstruct changes in rainfall gradients? Can these be quantified in terms of P-E changes through time?
10. Can we reconstruct the manner in which, Man/societies responded to climatic changes (i.e. rainfall changes) and landscape changes in the past? What were the reasons for the abrupt collapse of major civilizations and are there lessons to be learnt in terms of survival strategies?
11. How are extreme events processed through geomorphic changes? What are the time scales, thresholds and amplitudes of response of landforms to such changes?
12. Could there be new proxies (such as molecular or chemical indices, isotopic parameters, biological proxies) that could be developed to answer these questions? How reliable are speleothem and coral records given the recent consideration on their validity in respect of kinetic fractionation effects?
13. What teleconnections affect the monsoon system and can they (and their time dependence) be elucidated? How much does solar variability influence the monsoon?
14. Can regional climate models be developed to explain paleodata and hence aid in monsoon rainfall prediction?

Modeling and model data inter-comparison will be an area that will need substantive inputs. To an extent, poor regional scale resolution of Global Circulation Models (GCMs) does not capture spatial variability of the monsoon in sufficient detail and in our view, regional climate reconstruction that are nested in GCMs will be the only solution. We also need scenario building for future use. These will include modeling of sediment dynamics in basins, landscape dynamics, hydrological modeling, etc. These are not even thought of so far. There is also a need to integrate archeological data, societal data with paleodata to develop societal and economic scenarios of climate change. It will also be necessary to place all the data in a GIS format for ease of future planning. The time is now ripe to aim at a focused institutional frame work for climate change studies that will include basic sciences, adaptation and mitigation strategies, economic and policy issues and long-terms projections. Ignoring this will be at the expense of our PERIL.

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AK Singhvi would like to dedicate this article to the memory of his father, Dr. Achal Mal Singhvi, who always inspired him to do science of relevance and felt needs.

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Historical, Archeological, Dendroclimatological, Groundwater, Bore holes, Corals and Speleothems

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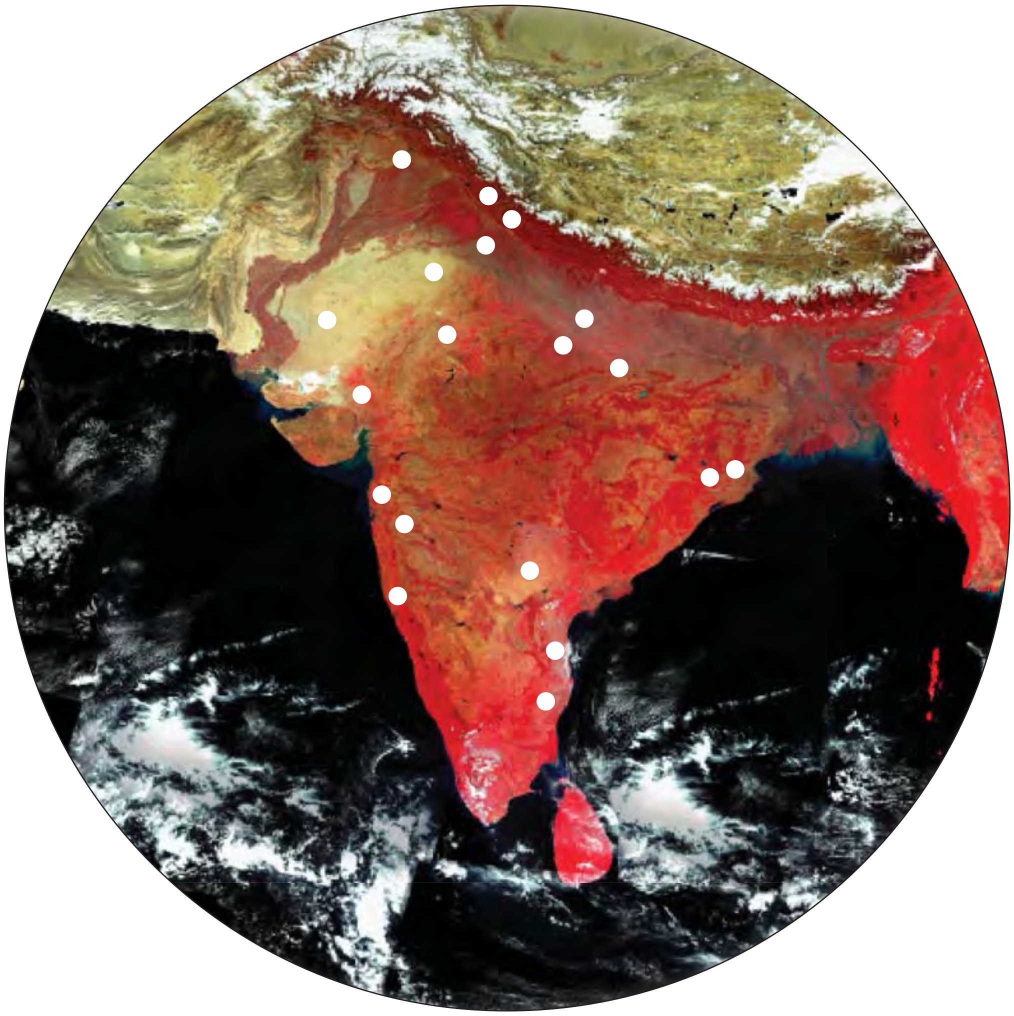

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