Climate change and monsoons: a paleo perspective

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I am a postdoc at the Max Planck Institute for Meteorology (MPI-M), Hamburg. I am studying the abrupt climate changes that occurred during the ice ages. I have obtained my Ph.D. at the Indian Institute of Science, Bangalore, under the supervision of Prof. J. Srinivasan and Prof. Arindam Chakraborty. In my doctoral thesis, I studied the evolution of the Indian monsoon over the last 22,000 years. I have been offered the Alexander von Humboldt postdoctoral fellowship to carry out further research at the MPI-M.

Abstract

"History repeats" goes a popular adage. Thus, by understanding monsoons in the ancient climates that are analogous to what is expected in the future, we can develop more confidence in the prediction of 21st century climate and be prepared accordingly. Monsoons of the distant past are inferred through indirect measurements, called proxies. Proxies suggest that monsoon strength has varied in step with periodic oscillations in the Sun-Earth geometry. These oscillations with periods 23 ky, 41 ky, and 100 ky (years – y, 1000 years - ky) modulate the solar radiation reaching the Earth. The growth and decay of ice sheets and the rise and fall of greenhouse gas concentrations in the atmosphere through the ice ages also modulate the monsoons. An emerging theory of monsoons known as "energetics of monsoons" can decipher the impact of these climate drivers and the ensuing feedbacks. We find that long-term monsoon evolution is determined by only two variables: the net energy flux into the atmosphere and water vapor. Furthermore, we have shown that the energy released by the oceans plays a crucial role in determining the local rainfall over the oceans. The anthropogenic global warming will enhance the moisture content in the atmosphere and lead to an increase in the monsoon rainfall.

Introduction: Why Paleo?

At 40 million years, the South Asian monsoon is probably as old as the Himalayas. However, a systematic measurement of the monsoon began only about 150 years ago, triggered by a series of climate disasters, one of which claimed nearly one-third of Orissa's population in 1866 [1]. Even though our society is more resilient today, monsoons continue to have an impact. Thus, it is of prime importance to produce a useful and reliable forecast. The ongoing global warming is driving the Earth system into uncharted territory. Hence, the 150 years of data is not sufficient to infer the full-scale impact of climate change on monsoons and society. Climate models have therefore been used. Our understanding of the magnitude and pattern of changes is limited by the uncertainties in the climate models used to make these future predictions. The Earth has been carrying out a natural experiment with its climate. Thus, studying the past will give us a clue about what to expect in the future. These ancient climates also serve as a test bench for the evaluation and calibration of the climate models, thereby improving our confidence in the simulated climate of the future.

With the advent of the satellite era in 1960, global meteorological data became available. This has been valuable in developing our understanding of the monsoon and its vagaries. Numerous factors that influence the monsoon have been identified, ranging from local processes to distant processes in the Indian, Atlantic, and Pacific oceans. The monsoon is not an isolated system — it also interacts with different components of the Earth system. Each component has a different timescale of influence [2]. Only a few interactions can be documented with only 60 years of global data. Studying climates of the past allows an inspection of the myriad possible interactions. Quantifying the role of these interactions provides a useful assessment of the dominant and important factors that drive monsoons and will be valuable in predicting how monsoons will evolve in the future.

Most of the theories of monsoons are based on present-day observations. A study of past monsoons thus has a significant role to play in testing these theories as well as in the articulation of their specifics. The land-sea thermal contrast theory of monsoon is no longer considered adequate as it cannot explain the monsoons that have been found to exist on aquaplanet simulations. Theories of shifts in the tropical band of precipitation based on energy and mass transport are gaining momentum. In this article, I will briefly discuss the techniques used to reconstruct ancient monsoons, followed by an overview of the monsoon variability on timescales beyond instrumental records. I will then highlight some of the limitations of proxies that can be overcome with climate models. Finally, I will discuss results from our work.

Reconstructing monsoons of the past

"If you listen carefully enough, the past whispers to you." – Albus Dumbledore (JK Rowling)

The monsoon is a phenomenal annual event that has an impact on the entire sub-continent as well as its biogeochemical cycles. The monsoon leaves behind biological, physical, and chemical signatures year after year. Some of these remain preserved in time. By reading such tell-tale signs, we can deduce monsoon features from a time before the instrumental record. These signatures are known as proxies and a few of them are listed below.

Cave data

Many caves contain structures known as speleothems (stalactites and stalagmites). Speleothems are made of calcium carbonate minerals. They grow over time due to the supply of calcium carbonate from rainwater that seeps through soil and drips into the cave. The isotopic composition of the rainwater is thus retained in the speleothems. Of particular importance is the heavier isotope of oxygen, ^{18}O, which preferentially condenses, leaving behind water vapor that is depleted in ^{18}O. Thus, as a parcel of air moves further into the monsoon domain, the ^{18}O isotope concentration diminishes every time rainfall occurs. When monsoons are strong, heavier precipitation renders the parcel of air excessively depleted in ^{18}O by the time it reaches the site of the cave. And vice-versa. This is known as the amount effect. Hence, ^{18}O concentration and monsoon strengths are inversely related. The ^{18}O depletion is measured with respect to a sample and is given by:

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) \times 1000 \,^{\circ}/_{\circ\circ} \qquad (1)$$

Figure 1 shows monsoon reconstruction from such a cave system in China. This reconstruction goes back to about 640,000 years.

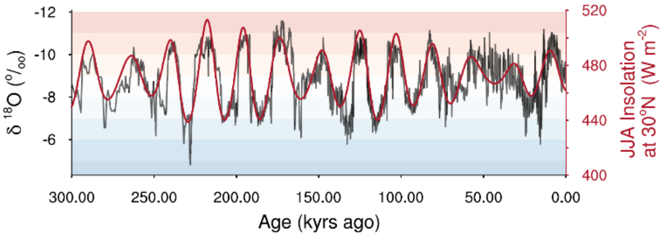

Figure 1: *The timeseries of $\delta^{18}O$ from the Chinese caves [3], shown by the grey line, and the incoming solar radiation during summer (Jun-Jul-Aug averaged) at 30°N, shown by the red line.*

Wind-based proxies

The low-level (near the surface) monsoon winds are an integral part of the monsoon system. They bring nutrient-rich deep waters into the upper layers along the coast of Oman and Somalia. Therefore, microscopic animals called foraminifers thrive in these waters during the monsoons. Stronger monsoons are associated with stronger winds, which, in turn, enhance the nutrient supply into the upper ocean and increase the foraminifer population in these waters. Thus, the cumulative amount of foraminifer in a season is proportional to the monsoon strength. Foraminifers develop calcium carbonate shells that precipitate on the seafloor when the foraminifer dies. A count of these shells from the seafloor sediment cores, thus, is a proxy for monsoon winds. During monsoon season, strong winds deposit dust into the ocean. A measure of dust concentration and grain size are continental indicators of monsoon strength.

Another source of wind-based data is from the loess deposits. Loess is formed by sedimentation of soil deposited by winds. Loess deposits, particularly from the Chinese loess plateau, have been used to understand the variations in monsoon winds. During winter, dust is deposited on the plateau when cold, dry winds from the north and northeast blow. Stronger winds can transport heavier and larger particles. The flux of dust into these regions also increases. Thus, the grain size and dust flux have been used as an indicator of winter monsoon strength. Furthermore, it has been demonstrated that magnetic susceptibility from the loess deposit represents the summer monsoon intensity, and wind direction can also be inferred.

Tree rings

Trees produce an annual layer of growth under their bark. The growth depends on the weather patterns of that year. Thus, by examining the width and density of wood in each ring, the climate variability over the lifetime of the tree can be discerned. Scientists have reconstructed a monsoon drought atlas from an extensive network of tree rings. Data such as this clearly shows the impact of volcanoes and decadal-scale oscillations in ocean temperature on the frequency and intensity of droughts. Both temperature and precipitation can also be reconstructed from isotopic variations in the rings.

Lake data

A qualitative estimate of the hydrologic conditions of the lake basin can be made with the help of ancient shorelines. Specifically, for closed lakes (with no outflow), the changes in a shoreline depend on the difference between precipitation and evaporation. Furthermore, the lake bottom sediments are formed continuously, thus, providing sequential information of variations in the sediments over time. These sediments could be of an origin outside the lake (e.g., pollen, sediments from rivers and streams, dust from winds, charcoal from forest fires, etc.,) or within the lake (e.g., fossilized shells of mollusks and foraminifers, precipitation of inorganic materials, etc.) The extent and type of paleo-vegetation cover around the lake can be estimated based on the pollen type and concentration. This is useful in understanding the hydrology of the period to which these pollens belong.

Marine sediments

The sediments on the ocean floor provide a wealth of information on ancient climates. There are numerous proxies, such as the flux of sediments brought by rivers, the abundance of foraminifera shells, and the isotopic compositions in the shells of various organisms that dwell near the surface and those that inhabit the seafloor, etc. The $\delta^{18}O$ from the foraminifer shells from sediment cores taken near the mouth of rivers can be used to estimate paleo-monsoon intensity. Since $\delta^{18}O$ in these waters is largely affected by the freshwater input from the river, variations in $\delta^{18}O$ reflect the variations in river run-off. This is, in turn, influenced by precipitation in the river catchment area. Thus, $\delta^{18}O$ from these sites can represent monsoon intensity. However, the $\delta^{18}O$ is also influenced by temperature. Other proxies such as alkenones can be used to make independent estimates of ocean surface temperatures. Some species of phytoplankton (microscopic plants) produce alkenones whose concentration is a function of temperature. The effect of temperature can thus be accounted for. The river run-off also contains leaf wax, washed off from the leaves of terrestrial plants further inland by monsoon rain. The δD (deuterium depletion) in these leaf waxes is a function of precipitation, and the isotopic ratio is preserved in the marine sediments.

The long-term variations in monsoons

With the help of various reconstructions of monsoons, we have gained insights into monsoon variability at timescales beyond instrumental records. Different factors, known as forcings, drive monsoon variability on different timescales.

Centennial and Millennial-scale (100–1000 years)

In the last millennia leading up to 1850 AD, when the industrial revolution began, the impact of human activities on climate was minimal. Variations in monsoon were driven by natural forcing agents, with the volcanoes being the most dominant forcing. Volcanic eruption leads to the formation of aerosols in the stratosphere that reflect solar radiation. This causes global cooling. A consequence of this is the reduction in monsoons in the years following the eruption. As the aerosols precipitate out of the stratosphere, global temperatures gradually rise and return to pre-eruption values in about a decade. Monsoon strength also increases to pre-eruption values. Volcanoes thus offer an impulse forcing to the climate system, and studying the response of monsoons and climate to this kind of forcing throws some light on its response to global cooling and warming.

The solar output is known to have centennial-scale fluctuations driven by the internal dynamics of the Sun. There is substantial evidence showing that the medieval warm period (900–1200 AD) was abnormally warm due to increased solar output. This was followed by a decrease in the solar output. This, coupled with volcanic eruptions, led to a colder climate between 1300 AD and 1850 AD, known as the little ice age. Glaciers extended further, and the winter snowline and sea-ice extent increased during this period. In general, the monsoon intensity has been found to follow these centennial oscillations in global temperature.

Several lines of evidence point to abrupt changes in climate in the distant past. The most recent event termed the “4.2 ka event,” has had a severe impact on the civilizations that existed around 4200 years ago. This event was relatively mild compared to those which occurred during the colder glacial periods known as the Dansgaard-Oeschger oscillations. Greenland ice cores have registered up to 10 K change in temperature within a decade. These abrupt changes last for multiple centuries to a millennium. These events are driven by factors internal to the climate system and are associated with the slowdown or speed up of the Atlantic meridional overturning circulation (AMOC). AMOC is a large-scale ocean circulation that moves warm water from the tropics to the poles. Fluctuations in AMOC have an impact on global climate, including monsoons. A strong correspondence of these abrupt events with monsoons has been recorded. In general, northern monsoons weaken, and southern monsoons strengthen [2]. This is a result of the southward shift of the monsoon rain bands. The ongoing global warming is melting Greenland ice sheets and also slowing down the AMOC. A sudden collapse of the ice sheet is considered to be a low probability event [4]. But should it occur, paleo records underscore strong global consequences, including a substantial weakening of the monsoons.

Orbital timescales (10 ky–100 ky)

As we move further back in time, the changes in the Sun-Earth geometry become pertinent. The Sun-Earth geometry varies on timescales ranging from 10 ky to 100 ky (ky – 1000 y) in a periodic manner known as the Milankovitch cycles. The strongest modes of variability occur at 23 ky, 41 ky, and 100 ky periods. These correspond to the precession of the Earth’s axis, the changes in the tilt of the Earth’s axis (obliquity), and the changes in eccentricity, respectively. These cycles impact the amount of solar radiation reaching the Earth. The 23 ky precession mode has the highest variability and is modulated by the low frequency 100 kyrs eccentricity mode. The 41 ky obliquity mode has a minor impact on monsoons as its effect on incoming solar radiation is highest at the poles and progressively decreases towards the equator. Many terrestrial reconstructions of monsoons indicate that monsoon strength has varied in step with the incoming solar radiation (Figure 1). During periods when the local incoming solar radiation is higher, monsoons are stronger, and vice versa.

On orbital timescales, the incoming solar radiation over the southern hemisphere is out of phase with that over the northern hemisphere. Thus, the monsoon records from the southern hemisphere should also exhibit an out-of-phase relation with their northern hemisphere counterparts. This is exactly what the cave data from Brazil indicate. In fact, the orbital pacing of monsoons is so consistent that orbital parameters evaluated from the astronomical calculations are used to determine the age model of the proxies. This technique is known as orbital tuning. The orbital pacing of monsoons is consistently observed in several proxies of monsoons, spanning all the monsoon domains [2].

The orbital variations in monsoon were previously explained with the land-sea contrast theory. Recently, the focus has shifted to the north-south movement of a thin east-west oriented band of rainfall called the intertropical convergence zone (ITCZ). ITCZ stretches in the east-west all the way across the planet and exports energy out of the warmer hemisphere and into the colder hemisphere. An increase in the differential warming of the hemispheres leads to a further shift in ITCZ into the warmer hemisphere. Thus, an increase in the incoming solar radiation in the northern hemisphere would lead to a northward shift in ITCZ and vice versa. A northward shift in ITCZ strengthens the monsoon, whereas a southward shift leads to a weakening of the monsoon. This theory has been useful in interpreting the variations in monsoon across continents recorded by the proxies.

Tectonic-scale (Millions of years)

The Earth's tectonic movement on timescales of millions of years leads to the opening and closing of ocean basins, the creation of mountains and valleys, etc. Such changes in the geography of the monsoon domain have an influence on the monsoon [5]. Evidence from climate models has highlighted that the Indian monsoon intensified due to the upliftment of the Tibetan Plateau 50 Ma (million years) ago. The CO_2 concentration was 3–4 times higher 50 Ma ago than today. There was a steady decline in the CO_2 concentration until 34 Ma when an ice age began. A corresponding decline in the monsoon strength has been recorded. This is undeniable evidence showing the impact of the greenhouse gases on monsoon.

What can climate models tell that proxies cannot?

Qualitative vs. Quantitative

Over the last couple of decades, an extensive network of proxy reconstruction of monsoon has been established. Since proxies do not measure rainfall directly but capture the effect of rainfall, most proxies cannot offer a quantification of changes in precipitation. This has rendered paleomonsoon reconstructions into a qualitative description of the monsoon. Hence, proxies should not be regarded as rain gauges. Furthermore, the physical basis of different proxies is not the same. The empirical relation between the physical process and proxy parameter depends on local processes—for example, the relation between precipitation rate and $\delta^{18}O$ in rainwater changes with the region. Thus, a comparison amongst proxies is not so straightforward.

Climate models are a useful tool to understand various climate processes as well as the impact of different forcings. With climate models, idealized thought experiments can be carried out to test theories and unravel mechanisms driving the climate processes. Numerous paleoclimate simulations have been carried out to understand the ancient climates. With the advent of paleo-simulations, quantification became possible. Such quantifications carry the potential of transforming qualitative explanations into a numerical model.

Point source of data – inconsistencies resolved with climate models

Despite the large agreement among proxies across continents regarding the orbital scale variability, they still are a point source of data. Traditionally, they have been thought to represent the large-homogeneous monsoon domain that they belong to. Several marine reconstructions of monsoon suggest that monsoon variations are out-of-phase with local incoming solar radiation, contrary to the terrestrial proxies of monsoon, which indicate a near in-phase variation of monsoon with incoming solar radiation. This has led to a long-standing debate in paleomonsoon literature [2].

Climate models provide a spatially continuous estimate of precipitation and a host of other meteorological parameters. The variations in the parameters associated with precipitation can also be studied. Whereas proxies record the total effect of all forcings, with climate models, sensitivity experiments can be carried out. Thus, the effect of forcing can be isolated. Being self-consistent, climate models provide a convenient way to quantitatively assess the impact of various feedback.

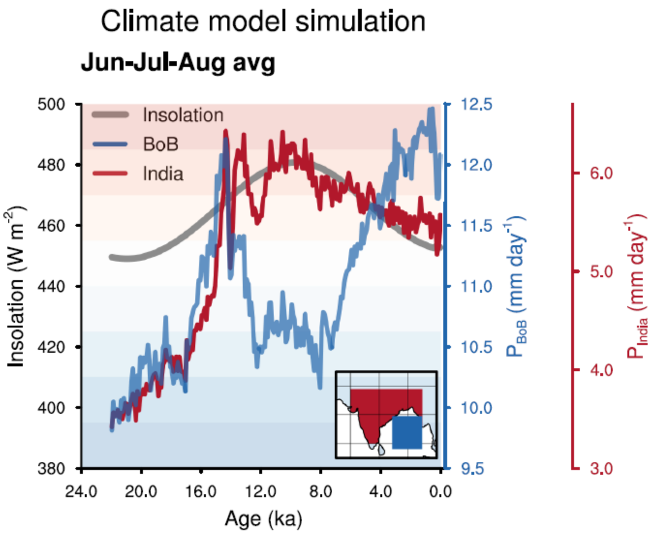

Figure 2: *The timeseries of summer (Jun-Jul-Aug mean) precipitation rate over India and the Bay of Bengal in red and blue respectively. The solid grey line represents summer incoming solar radiation averaged over the latitudes of India (10°–30°N) (image adapted from [6]). The precipitation rates are derived from climate model simulation of the last 22,000 years known as the TraCE-21k with realistic forcings.*

Using idealized as well as realistic experiments in the climate models, recent studies have underlined that monsoon response to changes in the Earth's orbit is opposite over land and oceans [6]. We have demonstrated that greenhouse gas forcing produces a relatively uniform monsoon response than orbital forcing [6]. During the period 22 ka to about 11 ka, climate moves from a the colder glacial to warmer interglacial [6, 7].

Greenhouse gases increase during this period. Hence, precipitation over India and the Bay of Bengal show similar variations. Across the period 11 ka to present, changes in the orbit are the dominant forcing, and precipitation over the two regions shows opposite trends. This suggests that the monsoon system, which was previously thought to be homogenous, consists of two distinct units, viz., the land and oceanic monsoon system. These have similar characteristics in the modern climate and respond identically to some forcings. But they behave differently in response to some other forcings.

The north-south shifts in ITCZ cannot explain this opposite response [6]. We have used a theory of monsoons based on the conservation of energy and moisture known as the "energetics of monsoons". This theory provides a simple diagnostic based on the total energy flux into the atmospheric column from the surface and top and total moisture content in the atmosphere.

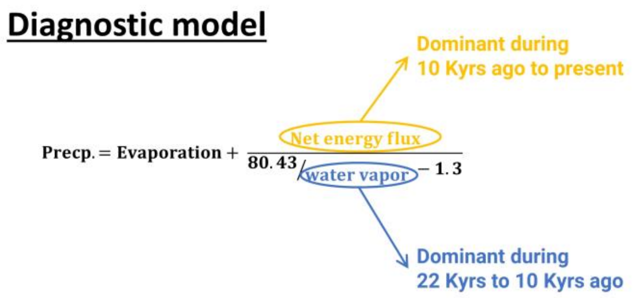

Figure 3: *A schematic showing the simple diagnostic equation of monsoon [6]. Different parameters are dominant during different periods depending on the type of forcing driving climate change.*

We have shown that feedbacks in response to changes in orbit are dominant over the ocean [8]. These feedbacks are in the form of surface energy fluxes and are large enough to counter the changes in the incoming solar radiation over the oceans. This leads to the opposite land-ocean response. Moreover, greenhouse gases affect the monsoon through their impact on water vapor. Since water vapor varies in a similar manner over land and oceans on these timescales, precipitation response is also similar.

Empirical relations change over time

Proxies are based on empirical relations observed in the modern climate, which is just one of the many possible realizations. These relations are assumed to be valid under all climates. Climate models allow an investigation of such empirical relations in different climates. They can, therefore, provide a basis for a better interpretation of the proxies. One such example is the wind-based proxies in the Arabian Sea. In the modern climate, there is a positive correlation between monsoon rainfall over India and the primary productivity in the western boundary of the Arabian Sea. As described in Section 2, this positive relationship has been the basis for some of the monsoon reconstructions. Using climate model experiments, we have shown that this relationship changes with changes in Earth's orbit [8]. The upwelling of nutrients in this region is related to factors other than the Indian monsoon rainfall. These factors are prominent on orbital timescales and are not relevant in modern observations. Therefore, our results suggest that these proxies should not be interpreted as variations in monsoon strength.

Discussion

Climate has played a crucial role in the evolution of modern humans. Only in the last century have the tables turned. Now it is the human activities that are driving climate change. This has put an enormous pressure on the ecosystem, which cannot adapt to the rapid pace of anthropogenic climate change. Therefore, a study of the past is crucial to understand how resilient the systems are and how fast they can recover (if at all they can).

In general, proxy-based evidence implies that global warming will lead to an increase in monsoon rainfall. The magnitude of change in the rainfall and the physical mechanism can only be determined with climate models. However, climate models suffer from shortcomings, foremost of them being the biases in sea surface temperature and precipitation. This could be a result of various parameterizations and/or certain missing feedback. One of the most studied biases in paleomonsoons is that of the underestimation of the intensity as well as the northward extent of the African monsoon 6000 years ago. This bias has been attributed to the missing vegetation feedbacks in the climate models. In a bid to overcome these issues, the resolution of climate model has been increased, and a wider range of processes incorporated. On longer timescales, other components of the Earth system, such as the cryosphere and the biosphere, impact climate and vice versa. However, accounting for these components and other processes runs the risk of increasing the complexity of the climate model without a guarantee of improving it. Despite these shortcomings, climate models are our best hope for understanding some key aspects of the past and future of monsoons.

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