MAUSAM, **52**, 1(January 2001), 275-284

551.583.2 : 551.513.1

Past monsoons : A review of proxy data and modelling

D. JAGADHEESHA and R. RAMESH

Physical Research Laboratory, Ahmedabad - 380 009, India

सार - अतीत के अधिकतम हिमानी युग (21,000 वर्ष पहले), से अब तक मानसून की तीव्रता के विकास पर जलवायु तंत्र के घटकों के मध्य आंतरिक पुनर्निवेश प्रणाली के योगदान की हाल के निदर्श अध्ययनों से पूरी जानकारी प्राप्त हुई है। इस शोध पत्र में भारत और उत्तरी अफ्रीका में ग्रीष्मकालीन मानसून से संबंद्ध इन निदर्श अध्ययनों की समीक्षा प्रस्तुत की गई है। इन अध्ययनों से पता चला है कि उत्तरी अफ्रीका में प्रारंभिक और मध्य होलोसीन के दौरान होने वाले केवल मौसमी आतपन परिवर्तनों से जल विज्ञानीय परिवर्तनों की प्रेक्षित सीमा स्पष्ट नहीं होती है। इस अवधि में प्रेक्षित परिवर्तनों की सीमा का अनुकरण करने के लिए जलवायु मॉडलों के सक्रिय घटक के रूप में वनस्पति को शामिल करना आवश्यक प्रतीत होता है। मॉडल के परिणाम दर्शाते है कि भारतीय क्षेत्र में आतपन और हिमनद युग धरातलीय सीमा की अवस्था में होने वाले परिवर्तन पर मानसून की अनुक्रिया निर्धारित करने में वर्षण मृदा नमी के पुनर्निवेशन का महत्वपूर्ण योगदान रहता है। 11 से 5 केए तक विषुवतीय प्रशांत महासागर में अचिरस्थायी उष्ण समुद्रतलीय परिस्थितियों से संबंधित सुझाव का निराकरण करने के लिए युग्मित महासागरीय वायुमंडलीय सामान्य परिसंचरण निदर्श प्रयोगों के सहयोजन से आरंभिक और मध्य होलोसीन के समय के प्रॉक्सी रिकार्ड के भारतीय मानसून की तीव्रता से संबंधित ऑकड़ों का भी उपयोग किया गया है।

ABSTRACT. Recent modelling studies have given insight into the role of internal feedback processes among components of the climate system on the evolution of monsoon strength since the Last Glacial Maximum (21,000 years ago). Here we present an overview of these modelling studies related to the summer monsoon over India and northern Africa. These studies indicate that the seasonal insolation changes alone do not explain the observed extent of hydrological changes during the early and middle Holocene over northern Africa. To simulate the extent of observed changes during this period incorporation of vegetation as an active component in climate models appears to be necessary. Over the Indian region, model results show that precipitation-soil moisture feedbacks play an important role in determining the response of the monsoon to changes in insolation and glacial-age surface boundary conditions. Indian monsoon strength from proxy records during the early and middle Holocene have also been used in conjunction with coupled ocean atmosphere general circulation model experiments to refute the suggestion that semi-permanent warm surface conditions prevailed over equatorial Pacific ocean from 11 to 5ka.

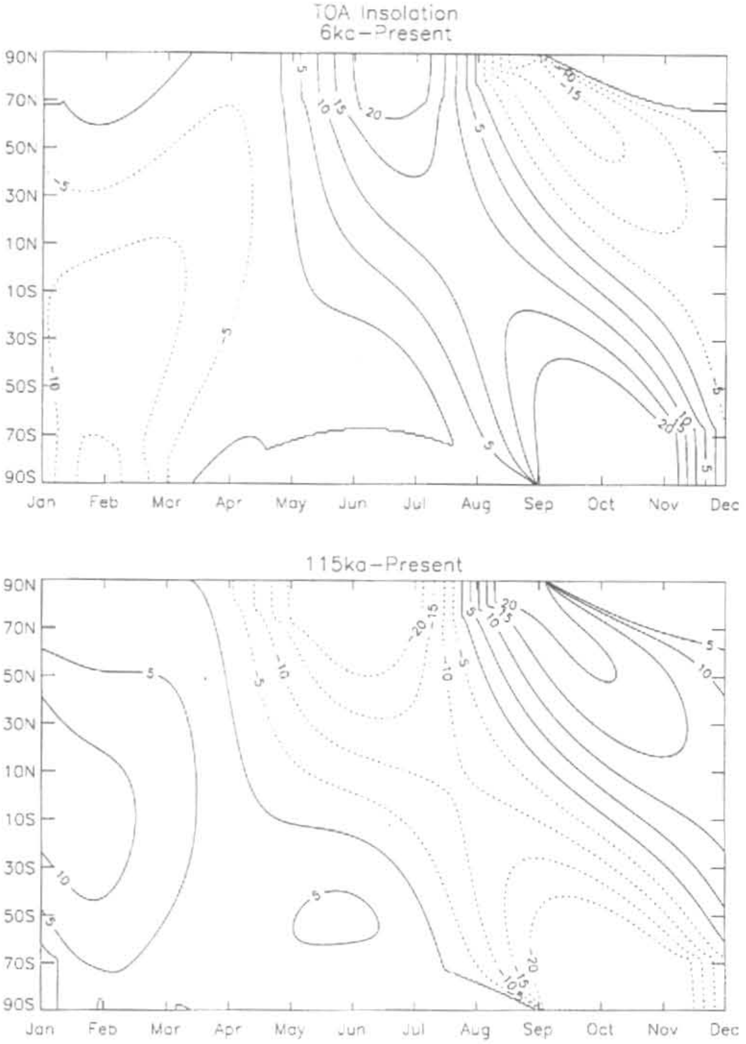
Key words – Palaeomonsoon, General circulation models, Insolation, Last glacial maximum, Mid-Holocene, Vegetation feedbacks.

1. Introduction

Palaeo indicators of monsoon strength from continental and marine sediments show that the monsoon strength over northern Africa and southern Asia varied on century to million year time scales. Observational analysis and modelling studies indicate that seasonal changes in insolation due to earth's orbital parameter changes, land-ocean distribution, tectonic changes, ice cover and sea surface temperature(SST) changes, atmospheric CO_2 concentration, aerosols, etc. are the factors responsible for the monsoonal changes (*e.g.* Prell and Kutzbach 1992, Sirocko 1996a). Many interesting inferences concerning the physical processes behind past monsoon variations of northern Africa and southern Asia since the Last Glacial Maximum (LGM) have come up as a result of modelling studies as well as reconstructions of the climatic boundary conditions (palaeo-data) in recent years. The purpose of this paper is to give a broad overview of these modelling studies. We mainly focus on the nature of processes and their role in determining past monsoon strengths as inferred from these studies.

2. Present monsoon over south Asia and northern Africa

It is important to know the characteristic features of present day monsoon, factors and processes responsible for its observed spatio-temporal variability in order to analyze the palaeoclimate model outputs meaningfully. Models are mainly used to infer the possible mechanisms of palaeoclimate changes due to strong changes in internal


TOA Insolation
6ka−Present

115ka−Present

Fig. 1. Insolation anamolies (W/m^2) for 6 ka and 115 ka with respect to present day

and external boundary forcings relative to present day. We note here certain important features of the south Asian and north African monsoons. It is well recognized that the monsoon circulation arises primarily as a result of differential heating of the atmosphere over land and ocean (*e.g.* Keshavamurthy and Sankar Rao 1992, Webster *et al.* 1998). Apart from this primary factor, there are other factors like orography, geographical distribution of land and ocean, Coriolis force, etc. which give distinct features to the monsoon circulation over different regions. The presence of Tibetan plateau to the north of India and its role as an elevated source of heat during summer is mainly responsible for the greater extent of the monsoon circulation over India than elsewhere. Many atmospheric general circulation model (AGCM) studies signify the importance of Tibetan plateau on Indian monsoon (Hahn and Manabe 1975, Prell and Kutzbach 1992).

The intraseasonal oscillations (ISO) *i.e.*, the northward propagation of the convection, with a period of a few days over southern Asia is the main process behind the greater northward extent of rainfall over this region. Over northern Africa ISO are weak and rainfall pattern is restricted to a relatively narrow latitude band. Low level south-westerly winds during summer season over the Indian ocean are also stronger than the westerlies over equatorial northern Africa. At upper levels the wind pattern is opposite to that of low level, characterized by strong easterlies from western Pacific to Africa also known as tropical easterly jet. Upper level circulation is also characterized by a broad anticyclonic circulation centered over the southern part of Tibet. Low level cross equatorial winds off the eastern coast of tropical Africa, known as Findlater jet, are an integral part of the Indian monsoon and no other monsoon region has such a strong.

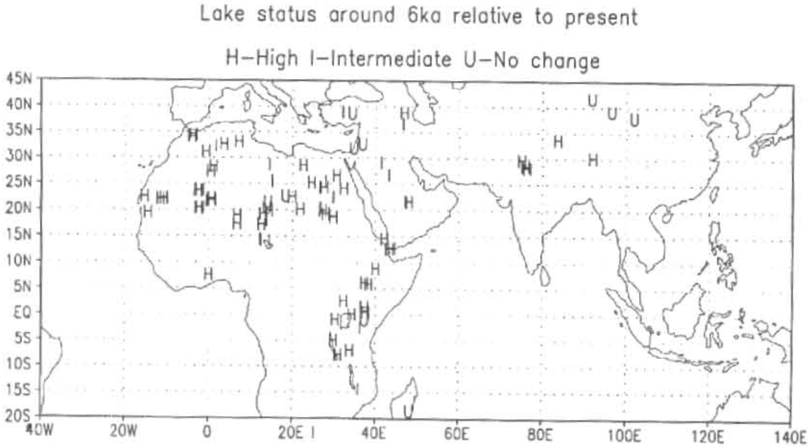


Fig. 2. Changes in lake level during 6 ka relative to present

cross equatorial flow. Globally, the upper level wind circulation is indicative of a broad scale divergent flow centered above the western Pacific with convergence centered over southern Africa. This pattern gives a broad scale measure of the Hadley-Walker circulations. Webster *et al.,* (1998) review the processes and factors such as El Nino Southern Oscillation (ENSO) events, Eurasian snow cover, etc., affecting the monsoon and its variability.

Modelling hindcast studies of the ENSO-SST anamolies on the Indian monsoon show that its predictability depends on model formulation as well as initial conditions. Thus there is some hope that predictability of the Indian monsoon may improve as model formulations improve; there is also an inherent noise hindering this predictability due to internal atmospheric dynamics. However, one can hope that at least large scale changes in the monsoon circulation such as observed in palaeoclimate records may be modelled with the knowledge of boundary forcings responsible for such changes.

3. Basis for past monsoon modelling studies

Our understanding of the present monsoon characteristics, palaeo indicators of monsoon strength and climatic boundary conditions like SSTs, glacial cover, vegetation etc., ability to calculate earth's orbital parameters which determine the insolation received by the climate system, and finally our ability to model the climate system form the major basis for palaeomonsoon modelling studies. We note some of the speculative arguments for past monsoonal changes based on knowledge of past climatic forcings, palaeo indicators of monsoon strength, processes and factors associated with present monsoon. These arguments are examined in detail by corroborative modelling studies.

On millenial time scales, insolation varies strongly due to variations in the orbital parameters of the earth. Fig. 1 shows top of the atmosphere (TOA) insolation changes during 6 and 115 ka relative to present day calculated using standard formulae (Berger and Loutre 1994). During 6(115) ka, northern summer insolation was approximately 5(8) percent higher(lower) relative to present. Definitely such periods are in strong contrast relative to present in external insolation forcing, and one can expect features of the monsoon circulation to be unique, at least on a broad scale to such strong changes in external forcings.

Of particular importance to the Indian monsoon is the role of internal factors like the snow cover over Eurasia and SST anamolies in the adjoining oceans. During LGM presence of large ice sheets split the high latitude jet streams resulting in enhanced equatorward cold winds. Such a change in atmospheric circulation may alter conditions over northern Africa, and Eurasia, resulting in more cooler conditions relative to present and hence decrease(increase) the summer(winter) monsoon strength during LGM.

One of the major strengths of modelling studies is that they hint at the possible role of internal factors like vegetation, SSTs, and the associated feedback processes in the monsoonal changes.

Thus, past monsoon modelling studies not only help in our understanding of the factors and processes influencing the monsoon, but also helps in testing whether the models are able to explain the large scale features of the past monsoonal changes.

4. Broad scale changes in Asian and African monsoons inferred from palaeoclimate proxies

Palaeomonsoon data over southern Asia and northern Africa clearly shows variations in monsoon strength from century to million year time scales. Pant and Rupa Kumar (1997) give a descriptive account of the present and past monsoons over South Asia. Here we restrict our discussion to broad scale changes in monsoon circulation to strong changes in external and internal boundary forcings relative to the present, inferred from the geological records. Over the continents, the majority of palaeomonsoon records is from geochemical and fossil pollen studies of lake sediments (*e.g.* Singh *et al.*, 1974, Bryson and Swain 1981, Wasson *et al.*, 1984, Street-Perrott *et al.*, 1989). The lake level records are broadly categorized in qualitative terms as high, intermediate and dry throughout geologic times for comparison with their present levels. Street-Perrott *et al.*, (1989) give the details of factors taken into account in this categorization. A majority of these records over northern Africa and southern Asia is from the areas where the present monsoon rainfall is weak or completely absent (Sahara, Arabia, north-western India and the Chinese monsoon region) and are mostly regions of transition from monsoonal to desert/extratropical climate. These records indicate that there is a widespread increase in lake levels during early and middle Holocene relative to present. Changes in lake status in qualitative terms for 6 ka is shown in Fig. 2. Over marine regions, upwelling indices such as foraminiferal species abundances, geochemical indicators of wind strength such as dust, pollen, *etc.*, are the major proxies (*e.g.* Van Campo *et al.*, 1982, Pokras and Mix 1985, Prell 1984, Sirocko 1996b, Sarkar *et al.*, 1990). Van Campo *et al.*, (1982) and Pokras and Mix (1985), using the wind blown fresh water diatom record extending up to 150 ka showed that equatorial north African lakes were drier at the time of glacial inception (115 ka). Prell (1984) reconstructed the monsoon upwelling intensity for several thousand years by measuring the abundance of *G. bulloides*, a species of foraminifera more abundant in cooler sea surface conditions. Such cooler surface conditions over this region are induced mainly by the southerly monsoon winds and hence abundance of *G. bulloides* is an indicator of southerly wind strength, also known as the Findlater jet. This index showed variations similar to that of northern hemisphere summer insolation, thereby indicating that the strength of the Findlater jet is mainly influenced by summer insolation. The extent of monsoon winds over the Arabian sea inferred from geochemistry of dust grains deposited in the ocean sediments reveal that the summer monsoon weakened during the LGM (≈ 21 ka), increased during early and middle Holocene (≈ 10 to 6 ka), and decreased to present extent in tandem with seasonal summer insolation and glacial surface conditions (Sirocko 1996b). Sirocko (1996b) also showed that glacial events over high latitude regions such as Younger Dryas(YD) around 10.5 ka do not seem to influence the summer monsoon winds over Arabian sea, as summer insolation was higher during this period while the signature of such events are strong in the winter monsoon proxies. However during the LGM, when insolation pattern was almost same as that of the present day, glacial conditions affected both the summer and winter monsoon winds to a great extent (*e.g.* Sirocko 1996b, Sarkar *et al.*, 1990). Thus it is likely that the competing influence of glacial conditions and summer insolation, that determine the strength of the Indian monsoon on millenial time scales. Clemens *et al.*, (1991), based on geochemical study of southern Indian ocean cores, concluded that apart from direct insolation forcing, internal forcing associated with latent heat transport from southern Indian ocean is also important. Glacial events such as YD were found to affect the north African summer monsoon even though the summer insolation was higher relative to present. This is due to the proximity of northern Africa to north Atlantic ocean which is the main supplier of moisture influx for this monsoon. A few records of the monsoon strength such as vegetation proxies from peat bogs from southern India have also been unearthed (Sukumar *et al.*, 1993).. More palaeoclimate proxies from both oceanic and continental regions over India during periods of stronger insolation changes relative to the present are needed for documenting major changes in oceanic and continental precipitation, and associated monsoon circulation. With the advent of AMS (Accelerator Mass Spectrometry) marine sediments are being dated with increased resolution (especially from coastal areas with rapid sediment accumulation). These studies have provided the details of the monsoon changes (e.g. P-E) during the transition from the LGM to Holocene (Sarkar *et al.* 1999, Somayajulu *et al.* 1998).

5. Modelling studies of past monsoon variations

Early palaeomonsoon modelling studies used relatively low resolution atmospheric general circulation models (AGCMs) in perpetual mode to simulate characteristic features of extreme summer and winter months (July and January) to changes in insolation and glacial boundary forcings (Prell and Kutzbach 1992). Some studies used very low resolution AGCMs in annual cycle mode or to simulate seasons (Gates 1976 ; Kutzbach and Otto-Bleisner 1982). These studies were in qualitative agreement with the palaeo indicators of

TABLE 1

Some of the models used in recent palaeomonsoon studies. Except CLIMBER2, all other models are AGCMs. Some AGCMs incorporate land surface model and some are also coupled to an ocean general circulation model(OGCM)

Model	Resolution	Features	Reference
UGAMP	T42, L19	Interactive surface hydrology	Dong *et al*. 1996
LMD4	48*36, L11	Bucket type soil hydrology	DeNoblet *et al*. 1996
CCM2	T42, L18	Coupled to a land surface model	Kutzbach *et al*. 1996
GEN2	T31, L18	Coupled to land surface and ocean circulation model	Kutzbach and Liu 1997
CCM3	T42, L18	Coupled to a land surface model	Brostrom *et al*. 1998
NCAR CSM	T31, L18	CCM3 synchronously coupled to an ocean GCM	Otto-Bliesner, 1999
GFDL	R30, L14	Coupled to GFDL global ocean model	Bush, 1999
CLIMBER2	51°× 10°	Climate-Biosphere model of intermediate complexity	Claussen *et al*. 1999

monsoon strength such as Arabian sea upwelling index (Prell, 1984) and supported the inference from proxy records that the summer monsoon intensity is primarily controlled by insolation changes at the precessional frequency of the earth's orbit (19 to 23 kilo years). They illustrated the changes in monsoon strength due to summer insolation changes by means of model derived large scale monsoonal indices such as averages of precipitation over the Indian and north African monsoon regions, pressure index (difference of mean sea level pressure averaged over the ocean and the land between 15°S to 45°N over the monsoon domain), southerly wind speed averaged over western Arabian sea, land surface temperatures, etc. The quantification of monsoon strength in these studies was thus on a large scale and reasonably explained the monsoon evolution on long time scales as due to a combination of tectonic, insolation, glacial conditions, and atmospheric CO_2 concentration (Prell and Kutzbach, 1992). But these studies did not take into account many internal feedback processes associated with soil moisture, precipitation, and snow cover. Some of the recent models which incorporate advanced treatment of surface hydrology and used in palaeoclimate modelling studies and their features are given in Table 1.

A relatively high resolution AGCM which incorporated interactive surface hydrology was used by Dong *et al*. (1996) to investigate the response of the atmospheric circulation to changes in insolation and glacial boundary conditions. The time period they studied were 6 and 115 ka (insolation changes and pre-industrial atmospheric CO_2 concentration) and 21 ka (CLIMAP (1981) surface boundary conditions and atmospheric CO_2 concentration). They found that the monsoon strengthened(weakened) due to changes in insolation during 6(115) ka and weakened substantially during the LGM. These results are in qualitative agreement with previous studies. However there are many important differences, due to the incorporation of interactive surface hydrology and also due to a relatively higher model resolution. Some of the major results of this study are :

(*i*) The change in precipitation-evaporation (P-E) is similar to the change in precipitation (P) in all the cases. During 6 ka, the onset of monsoon was quite rapid and there was a positive feedback between precipitation and soil moisture. The increase in insolation was able to offset the effect of relatively cooler conditions during winter and spring. During 115 ka reduced spring and summer insolation reduced the land-sea thermal contrast resulting in increased snow cover, and cooler temperatures over Eurasia, which delayed the onset of monsoon and its subsequent evolution was also weakened because of the decreased summer insolation.

(*ii*) For 21 ka, there was a large reduction of precipitation over northern Africa and India. The reduction in precipitation was mainly brought about by increase in Eurasian snow cover, a large scale drying of the atmosphere due to cooler SSTs and surface air temperatures. The model atmospheric kinetic energy over southeast Asia was remarkably lower during this period compared to present, 6 and 115 ka.

(*iii*) The model results support the hypothesis that both insolation as well as glacial conditions affect the monsoon strength. But unlike the previous AGCM sensitivity studies done by Prell and Kutzbach (1987), where the effect of these factors were found to be additive, this study supports view of Clemens *et al.* (1991), who, based on the geochemical evidence from the southern Indian ocean sediment cores, suggested that a large part of the Indian summer monsoon variability is not only due to the direct insolation changes, but also due to the internal forcing associated with the latent heat transport from the southern Indian ocean. Prell and Kutzbach report a rather modest decrease in summer monsoon rainfall (-20%) over India for LGM whereas this study indicates that the largest change in summer monsoon rainfall (-64.44%) takes place during LGM. These differences from previous modelling studies are related to incorporation of interactive hydrology and may also be due to higher model resolution compared to that of Prell and Kutzbach (1992).

In another study, DeNoblet *et al.*, (1996), using a relatively lower resolution AGCM for the insolations of present day, 6, 115, and 126 ka, focussed on sensitivity due to insolation changes alone keeping all other boundary conditions the same as that of the present day. The major inferences from this study were

(*i*) Insolation induced increase(decrease) of the land-sea thermal contrast during 6 and 126 ka(115 ka) induces a major shift of convergence zone associated with the monsoon towards northwest (southeast), resulting in increase(decrease) of precipitation over land of monsoon regions at the expense of decrease(increase) of precipitation over the ocean. They point out that such shifts in convergence zones are observed during weak/strong monsoon events of the present day monsoon due to El Nino/La Nina.

(*ii*) The model response to insolation changes is such that the frequency of high rainfall events increases(decreases) due to increase(decrease) in monsoon strength induced by summer insolation increase (decrease) which is also a characteristic feature of years of strong(weak) rainfall of the present day.

Jagadheesha *et al.* (1999), studied the impact of horizontal resolution using community climate model version 2 (CCM2) AGCM to strong changes in insolation and showed that the high (low) horizontal resolution is more sensitive to decrease (increase) in insolation due to the differences in the depiction of surface energy between the two resolutions in their present monsoon simulations. They found that though the model gives some climatological quantities like P and P-E almost similar on a continental scale in both the resolutions in the present monsoon simulation, the similarity does not persist when insolation changes significantly from present values. Thus some differences in the model sensitivities arise just because of different horizontal resolutions. Shown in Fig. 3 as an illustration are July mean 200hPa velocity potentials for the present, 6 ka and 115 ka obtained from multi-year integrations of CCM2 AGCM by the authors. It can be noticed that there are shifts in convergence centers towards west(east) for 6(115) ka due to increases(decreases) in summer insolation relative to present.

Intercomparison of various modelling studies began with the inception of Palaeoclimate Modelling Intercomparison Project (PMIP) (Joussaume and Taylor, 1995) in which results from models of diverse formulations under common boundary forcings were examined. Inter-model comparison studies are very useful as they have the potential to indicate whether, any characteristic feature of the simulation is specific to the model or is likely to be a robust response of the climate system. These studies reveal the role of model formulations such as horizontal resolution, differences in the simulation of present day climate, and physical parameterizations on the model sensitivity and come up with the most probable candidate mechanisms behind climatic changes. In one such study Joussaume *et al.*, (1999) compare sensitivities of monsoonal climates over northern Africa and southern Asia to 6 ka insolation in 18 participating models of PMIP. This comparison shows that all the models show a northward expansion of rainbelts over south Asian and north African regions, and underestimate the northward extent of rainfall over

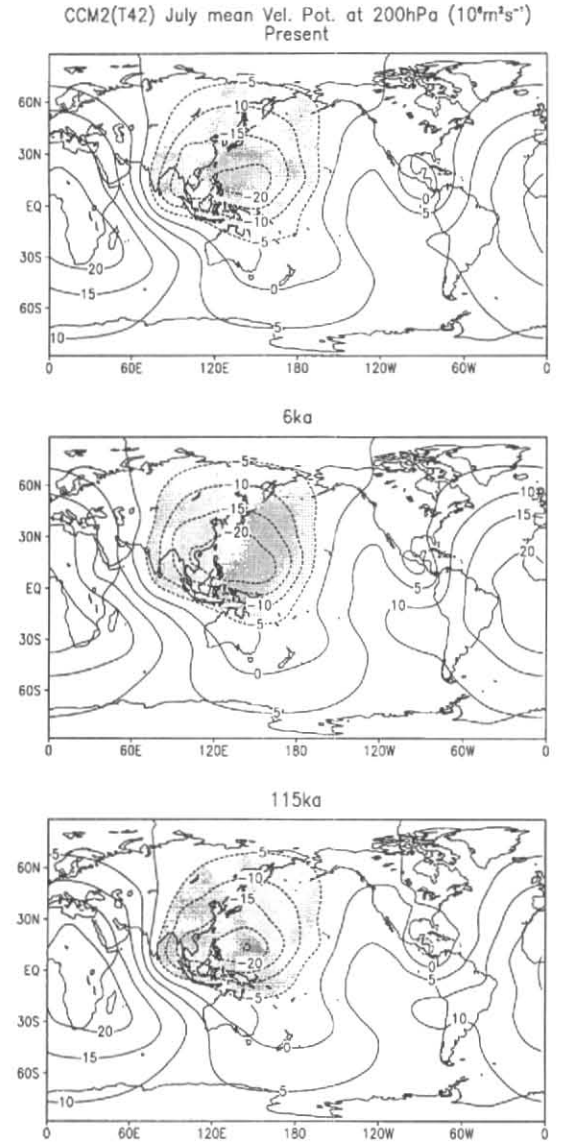


Fig. 3. July mean velocity potentials (Vel. Pot.) at 200hPa for present, 6 ka and 115 ka orbital parameters obtained from multi-year integrations of CCM2(T42) AGCM

northern Africa for 6 ka. Kutzbach *et al.*, (1996) using CCM2 AGCM coupled to a land surface model found that the inclusion of orbital parameters alone does not explain the extent of hydrological and vegetation changes over northern Africa, and the sensitivity increases with the inclusion of vegetation of 6 ka as inferred from palaeo records, but still inadequate to explain the observed northward extent of vegetation and precipitation. Kutzbach and Liu (1997) find that the inclusion of oceanic feedbacks using a coupled ocean atmosphere GCM gives higher rainfall over northern Africa during 6 ka than any of the previous experiments, but still not adequate to explain the observations. A detailed study of land surface feedbacks associated with palaeo vegetation, and lakes and wetlands, during 6 ka using CCM3 AGCM which incorporates a land surface model also shows that none of these factors gives the observed northward extent of vegetation and expansion of lakes (Brostrom *et al.*, 1998). Thus additional feedback processes may be necessary to explain the extent of rainfall over northern Africa as seen in palaeoclimate reconstructions. Joussaume *et al.*, (1999) point out that the data-model discrepancies over northern Africa may be due to the omission of synergistic interaction between ocean, vegetation and surface-water storage. To examine this hypothesis more modelling and Intercomparison studies are required. The recent work of Ganopolski *et al.*, (1998) using a climate biosphere model of intermediate complexity wherein synchronous coupling between vegetation and atmosphere-ocean circulation is incorporated, indicates that the explanation of observed extent of hydrological and vegetation changes over northern Africa during middle Holocene requires vegetation-atmosphere feedbacks. Using the same model Cluassen *et al.*, (1999) arrived at an interesting explanation for the abrupt desertification of northern Africa around 5 ka. They performed transient simulations from 9 ka to present starting from the surface and oceanic boundary conditions of 9 ka obtained from an equilibrium simulation of 9 ka. The only input forcings for their model were insolation and CO$_2$ and the rest of the parameters such as vegetation etc. are interactively calculated in the model. More importantly vegetation interacts synchronously with the climate and *vice versa* in their model. The transient simulations from this model showed that the rapid desertification occurred around 5 ka within a few hundred years. They argued that the Saharan and Arabian desertification were triggered by subtle decreases in insolation which were strongly amplified by vegetation-atmosphere feedbacks. This study also implies that the vegetation-atmosphere interaction is more important than oceanic changes in causing desertification, thereby supports and extends the Charney's (1975) pioneering work on desertification. However, due to the coarse resolution ($5^{o}\times10^{o}$) this model does not adequately distinguish changes over western and eastern Africa. Hence additional studies are required with comprehensive AGCMs which include this feedback so as to assess this result and its geographical significance.

While vegetation-atmosphere feedbacks are important for explaining past north African monsoon, past Indian monsoon strength due to insolation changes have implications on questions related to past ENSO events. Some researchers based on geoarchaeological evidence and faunal indicators of warm conditions suggest the existence of semi-permanent warm conditions typical of present day El Nino events in the equatorial eastern Pacific along with an absence of interannual variability from 11 ka to 5 ka (Rollins *et al.*, 1986, Sandweiss *et al.*, 1996, DeVries *et al.*, 1997). Bush(1999) uses an AGCM forced by fixed SSTs and also couples it to an ocean general circulation model to test the possibility of existence of such semi-permanent warm conditions over the eastern equatorial Pacific during Mid-Holocene (6 ka). He finds that when the model is forced with SST distribution typical of warm ENSO events with 6 ka orbital parameters, there is a drastic reduction in Indian monsoon rainfall contrary to observations inferred from proxies. When AGCM is coupled with OGCM and run with 6 ka orbital parameters, Indian monsoon intensifies and the Walker circulation strengthens which in turn interacts dynamically with the equatorial eastern Pacific resulting in enhanced upwelling and more La Nina-like situations. Another similar study by Otto-Bliesner (1999) using NCAR Climate System Model (CSM) which is a synchronously coupled atmosphere-land-ocean-sea ice model suggests that the frequency and strength of El Nino events during 6 ka remained similar to that of present day. He suggests that faunal indicators of warmer conditions developed in narrow embayments and are not representative of large scale sea surface conditions like ENSO.

6. Concluding remarks

Proxy records as well as modelling studies have revealed many important clues regarding the variability of past monsoon strength over India and northern Africa since the LGM as well as raised important issues to be assessed in detail by modelling studies. Northern Africa appears to be governed by synchronous vegetation-atmosphere interactions triggered by gradually varying insolation changes. It also calls for assessment of vegetation-atmospheric interactions incorporated in the climate models. The strength of vegetation feedbacks on the state of the atmosphere-ocean circulation needs to be studied by using climate models in order to assess the importance of this feedback on the evolution of the monsoon at other regions apart from northern Africa. Future modelling studies are likely to address the vegetation-atmosphere feedbacks in more detail. These studies have implications on modelling of future climate due to enhancement of atmospheric greenhouse gases as these studies have not taken into account these feedback processes. Crowley and North (1991) while summarizing data model agreement and discrepancies note that for mid-Holocene, models adequately explain tropical monsoonal changes, and fail to explain high latitude climate changes and for LGM, models adequately simulate high latitude climate and fail to simulate tropical aridity. Recent modelling studies improved the data-model agreement for the LGM. For early and middle Holocene, the AGCM sensitivities decrease from earlier studies in many cases because of changes in model formulations such as horizontal resolution and physical parameterizations (Kutzbach *et al.*, 1996) and calls for incorporation of additional feedback processes associated with vegetation and other surface conditions.

Acknowledgements

We thank SERC-IISc for computational support on IBM SP2. Lake level data for 6 ka is taken from the National Geophysical Data Center (NGDC) of NOAA, USA (Internet address - http://www.ngdc.noaa.gov/paleo). Figs. 2 and 3 are produced using GrADS software of Centre for Ocean-Land-Atmosphere Interactions, Department of Meteorology, University of Maryland, USA.

References

Berger, A. and Loutre, M.F., 1994, "Precession, Eccentricity, Obliquity, Insolation and Paleoclimates", *Long-Term Climatic Variations Data and Modelling*, Eds. J. C. Duplessy and M.C. Spyridakis, Springer-Verlag, 107-151.

Brostr"om, A., Coe, M., Harrison, S. P., Gallimore, R., Kutzbach, J.E., Foley, J., Prentice, I. C. and Behling, P., 1998, "Land surface feedbacks and palaeomonsoons in northern Africa", *Geophys. Res. Lett.*, **25**, 3615-3618.

Bryson, R.A. and Swain, A.M., 1981, "Holocene variations of monsoon rainfall in Rajasthan", *Quat. Res.*, **16**, 135-145.

Bush, A.B.G., 1999, "Assessing the impact of Mid-Holocene insolation on the atmosphere-ocean system", *Geophys. Res. Lett.*, **26**, 99-102.

Charney, J.G., 1975, "Dynamics of deserts and droughts in the Sahel", *Quat. J. R. Met. Soc.*, **101**, 193-202.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., and Pachur, H.J., 1999, "Simulation of an abrupt change in Saharan vegetation in the mid-Holocene", *Geophys. Res. Lett.*, **26**, 2037-2040.

Clemens, S., Prell, W., Murray, D., Shimmield, G. and Weedon, G., 1991, "Forcing mechanisms of the Indian Ocean monsoon", *Nature*, **353**, 720-725.

CLIMAP Project Members, 1981, "Seasonal reconstruction of earth's surface at the last glacial maximum", *Geol.Soc.Am.Map.Chart.* Ser., MC-36.

Crowley, T.J. and North, G.R., 1991, Palaeoclimatology, Oxford University Press Inc., p 339.

DeNoblet, N., Braconnot, P., Joussaume, S. and Masson, V., 1996, "Sensitivity of simulated Asian and African summer monsoons to orbitally induced variations in insolation", *J. Geophys. Research.*, **98**, 7265-7287.

DeVries, T.J., Ortlieb, L., Diaz, A., Wells, L. and Hillaire-Marcel, C., 1997, "Determining the early history of El Nino", *Science*, **276**, 965-966.

Dong, B., Valdes, P.J. and Hall, N.M.J., 1996, "The changes of monsoonal climates due to earth's orbital perturbations and ice age boundary conditions", *Paleoclimates*, **1**, 203-240.

Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V. and Petoukhov, V., 1998, "The Influence of Vegetation-Atmosphere-Ocean Interaction on Climate During the Mid-Holocene", *Science*, **280**, 1916-1919.

Gates, W.L., 1976, "The numerical simulation of ice-age climate with a general circulation model", *J. Atmos. Sci.*, **33**, 1844-1873.

Hahn, D.G. and Manabe, S., 1975, "The role of mountains in the South Asia monsoon circulation", *J. Atmos. Sci.*, **32**, 1515-1541.

Jagadheesha, D., Nanjundiah, R.S. and Ramesh, R., 1999, "Orbital forcing of monsoonal climates in NCAR CCM2 with two horizontal resolutions", *Palaeoclimates*, **3(4),** 279-301

Joussaume, S. and Taylor, K.E., 1995, "Status of Paleoclimate Modelling Intercomparison Project (PMIP) ", In Proceedings of the First International AMIP Scientific Conference, WCRP, **92**, 425-430.

Joussaume, S. and 35 others, 1999, "Monsoonal changes for 6000 years ago: Results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP) ", *Geophys. Res. Lett.*, **26**, 859-862.

Keshavamurthy, R.N. and Sankar Rao, M., 1992, The Physics of Monsoons, Allied Publishers Ltd., India, p 199.

Kutzbach, J.E. and Otto-Bleisner, B.L., 1982, "The sensitivity of African Asian monsoon climate to orbital parameter changes for 9000 years B.P. in a low-resolution general circulation model", *J. Atmos. Sci*, **39**, 1177-1188.

Kutzbach, J.E., Bonan, G., Foley, J. and Harrison, S., 1996, "Vegetation and soil feedbacks on the response of the African monsoon to forcing in the early and middle Holocene", *Nature*, **384**, 623-626.

Kutzbach, J.E. and Liu, Z., 1997, "Response of the African monsoon to orbital forcing and ocean feedbacks in the middle Holocene", *Science*, **278**, 440-443.

Otto-Bleisner, B.L., 1999, "El Nino/La Nina and Sahel precipitation during the middle Holocene", *Geophys. Res. Lett.*, **26**, 87-90.

Pant, G.B. and Rupa Kumar, K., 1997, "Climates of South Asia". John Wiley and Sons Ltd., p 320.

Pokras, E.M. and Mix, A.C., 1985, "Eolian evidence for spatial variability of late Quaternary climates in tropical Africa", *Quat. Res.* NY, **24**, 137-149.

Prell, W.L., 1984, "Monsoonal Climate of the Arabian Sea during the late Quaternary: A response to changing solar radiation", Milankovich and Climate, Eds. Berger A. *et al.*, Reidel, 349-366.

Prell, W.L. and Kutzbach, J.E., 1987, "Monsoon variability over the past 150,000 years", *J. Geophys. Res.*, **92**, 8411-8425.

Prell, W.L. and Kutzbach, J.E., 1992, "Sensitivity of the Indian Monsoon to forcing parameters and implications for its evolution", *Nature*, **360**, 640-652.

Rollins, H.B., Richardson III, J.B. and Sandweiss, D.H., 1986, "The birth of El Nino: Geoarcheological evidence and implications", *Geoarchaeology: An international journal*, **1**, 3-15.

Sandweiss, D.H., Richardson III, J.B., Reitz, E.J., Rollins, H.B. and Maasch, K.A., 1996, "Geoarcheological evidence from Peru for a 5000 years BP onset of El Nino", *Science*, **273**, 1531-1533.

Sarkar, A., Ramesh, R., Bhattacharya, S.K. and Rajagopalan, G., 1990, "Oxygen isotopic evidence for a stronger winter monsoon current during the last glaciation", *Nature*, **343**, 549-551.

Sarkar, A., Ramesh, R., Somayajulu, B.L.K., Agnihotri, R., Jull, A.J.T. and Burr, G.S., 2000, "High resolution Holocene omonsoon record from the Eastern Arabian Sea", *Earth. Planet. Sci. Lett.*, **177**, 209-218.

Singh, G., Joshi, R.D., Chopra, S.K. and Singh, A.B., 1974, "Late Quaternary history of vegetation and climate of the Rajasthan desert, India", *Philos. Trans. R. Soc. Lond.*, **267**, 467-501.

Sirocko, F., 1996a, "Past and Present Subtropical Monsoons", *Science*, **274**, 937-938.

Sirocko, F., 1996b, "The evolution of the monsoon climate over the Arabian Sea during the last 24,000 years", Palaeoecology of Africa and the surrounding islands, **24**, 53-69.

Somayajulu, B.L.K, Agnihotri, R., Dixit, M., Dutta, K. and Sharma, C., 1998, "Arabian Sea sediments and palaeoclimates", Global Change Studies, eds. B. H. Subbaraya *et al.*, 207-221.

Street-Perrott, F.A., Marchand, D.S., Roberts, N.S. and Harrison, S.P., 1989, "Global Lake-Level Variations from 18000 to 0 Years Ago : A Paleoclimatic Analysis", Technique Report of Department of Energy, USA.

Sukumar, R., Ramesh, R., Pant, R.K. and Rajagopalan, G., 1993, "A $\delta^{13}C$ record of late Quaternary climate change from tropical peats in southern India", *Nature*, **364**, 703-706.

Van Campo, E., Duplessy, J.C. and Rossignol-Strick, M., 1982, "Climatic conditions deduced from a 150-kyr oxygen isotope-pollen record from the Arabian sea", *Nature*, **296**, 56-59.

Wasson, R.J., Smith, G.I. and Agarwal, D.P., 1984, "Late Quaternary sediments, minerals, and inferred geochemical history of Didwana lake, Thar Desert, India", *Paleogeo. Paleoclim. Paleoeco.*, **46**, 345-372.

Webster, P.J., Magana, V.O., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M. and Yasunari, T., 1998, "Monsoons: Processes, predictability, and the prospects for prediction", *J. Geophys. Res*, **103**, 14451-14510.