Centennial scale variations in monsoonal rainfall (Indian, east equatorial and Chinese monsoons): Manifestations of solar variability

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Studies dealing with variability of the Indian monsoon rainfall have been an active area of research since long due to their heavy impact over agricultural output on which a major proportion of the world's population survives. Several forcing factors dominating moonsoonal intensity have been proposed in the recent times[1], with solar forcing as one of them. In this article, we review most of the recent literature invoking impact of solar variability on monsoonal climate around the globe. This comparative study led us to propose that solar variability has to be carefully monitored in decadal to multi-decadal timescale, in conjunction with other greenhouse parameters, in order to achieve predictive capability of monsoon rainfall.

Introduction to sun–climate relationship

HISTORICAL climatic fluctuations of the late Holocene, viz. Little Ice Age (LIA) and Medieval Warm period (MWP) have been attributed to both internal (volcanic activity) and external forcings (variations in solar activity)[2]. In addition, it has also been suggested that subtle changes/reorganization in states of deep-water formation in the North Atlantic and Southern Ocean could be the forcing mechanism behind the observed LIA and MWP[3]. Eddy[4] carried out a detailed study dealing with comparison of solar activity inferred from sunspot activity and climatic history of the earth on centennial timescales during the last millennium; an extremely good correlation between these two led him to put forward his famous hypothesis of sun–climate relationship[5]. Since the beginning, a quantitative estimate of the sun–climate relationship has been debated, as total changes in solar activity in decadal/centennial timescale are generally thought too small (0.1–0.26%) to cause significant impact on the climate of the earth[6,7]. Nonetheless, suggestions were made that small solar-activity changes on centennial or multi-decadal timescales, coupled with several feedback mechanisms, viz. changes in budgets of water vapour, ice cover, albedo, etc. could have a cumulative effect causing significant changes in regional climate[8,9]. As a result, numerous recent studies[10–16] have demonstrated that centennial scale variability in solar activity has a significant impact on regional climate and could have caused severe droughts and floods in the past. An important question, however remains to be addressed, i.e. interrelation among observed climatic fluctuations at different locales around the globe in response to solar-activity changes during the last millennium. Knowledge of such links/relationships is crucial to studies making an attempt to quantitatively estimate solar forcing component of total radiative forcing on recent climate in the presence of greenhouse gases.

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Index of solar variability

Most studies invoking solar impact on regional climate used atmospheric ^{14}C variations in tree rings as an index of solar activity[11,12,14]. This is based on the fact that atmospheric ^{14}C oscillations are modulated by intensity of solar cosmic rays (SCRs); increasing atmospheric ^{14}C concentration during low solar-activity periods[17]. A direct index of solar forcing, however, is total solar irradiance (TSI). The yearly data of TSI for the last two decades are available from satellite measurements. Annual TSI record was reconstructed since AD 1610 based on parametrization of sunspot darkening and facular brightening[18]. Recently, the TSI reconstruction has been extended to AD 843 based on a quantitative estimate of common variations in the production rates of ^{14}C and ^{10}Be (ref. 19). Four TSI curves have been reconstructed for the last millennium, based on different scaling factors to match the total reduction in the solar output during the Maunder minimum. Reconstructed TSI curve shown in Figure 1 *a*, assumes 0.25% reduction in solar irradiance (with respect to the present) during the Maunder minimum[19].

Evidence for solar forcing on Indian monsoon

Our recent work[15] demonstrated solar influence on the intensity of the Indian monsoon using proxy data of surface

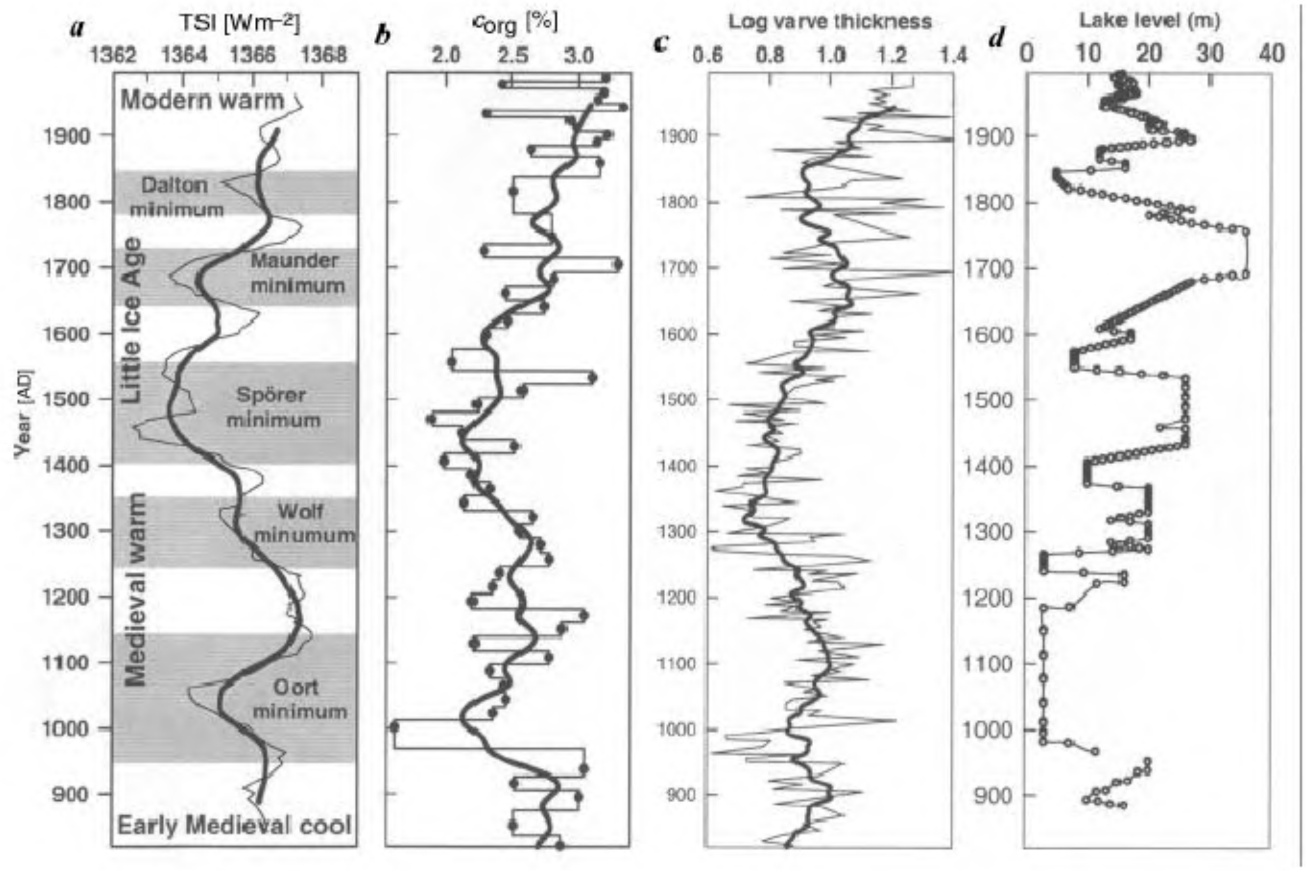

Figure 1. Visually-matched patterns of TSI variability (***a***), C_{org} (proxy for surface productivity and hence monsoonal intensity; ref. 15) (***b***), varve thickness (ref. 10) (***c***) lake level fluctuations in east equatorial region (ref. 11) (***d***) during the last millennium.

productivity (C_{org}) and continental run-off (Al) of a sediment core 2502G (21.8°N 68°E, dating back to ~1200 years) from the northeastern Arabian Sea. Sedimentary C_{org} was used as a proxy for surface productivity and monsoonal intensity[15]. The intensity of the Indian monsoon was found to have decreased during periods of solar minima of the last millennium[5] (Figure 1 *a*, *b*). In general, the intensity of the Indian monsoon was found to have increased during the MWP (~ AD 1050 to 1300) relative to that during the LIA ~ AD 1450 to 1750). Thereafter, monsoonal intensity seems to show a steady increase since ~ AD 1750 to present. These results were found spatially and temporally consistent by reinvestigating monsoonal intensity variations inferred from the varve thickness data from a sediment core off Pakistan in the northeastern Arabian Sea[10]. Reconstructed monsoon intensity variations inferred from this high-resolution varve thickness record also show a fairly matching pattern to that of reconstructed TSI during the last millennium (Figure 1 *a*–*c*), reinforcing our contention of solar control on intensity of the Indian monsoon. Solar impact on Indian monsoon intensity was established using both visual pattern matching as well as spectral analysis, which revealed significant periodicities of ~200, 110, 70 and 55 years in proxy data of Indian monsoon intensity. These cycles of monsoon activity were attributed to solar forcing as TSI data based on parametrization of sunspot counts, available for the last ~400 years[18] also revealed significant periodicities of 194, 113, 77 and 53 years[15].

Tridecadal behaviour of Indian monsoon

Annual data for All India summer monsoon rainfall[20] (AISMR; from AD 1813 to 1994) were subjected to 20-year running average; the data obtained were plotted against time as shown in Figure 2. A prominent ~60-year cycle is revealed, which coincides with ~55-year cycle present in monsoonal proxies of the northeastern Arabian Sea (C_{org} and log varve thickness data; refs 15 and 10 respectively). These observations prompt us to suggest that the observed ~60-year monsoon cycle could be driven by solar variability. Mehta and Lau[8] observed presence of a 11-year cycle in both TSI and Indian summer monsoon rainfall data; however, they could not fund any coherency between them. Thus, the well-known 11-year solar cycle does not seem to be directly controlling the Indian summer monsoon rainfall, but multi-decadal solar cycles (~60, ~100, ~200 years) involving 0.1–0.3% changes in TSI may have a cumulative effect on land–ocean thermal

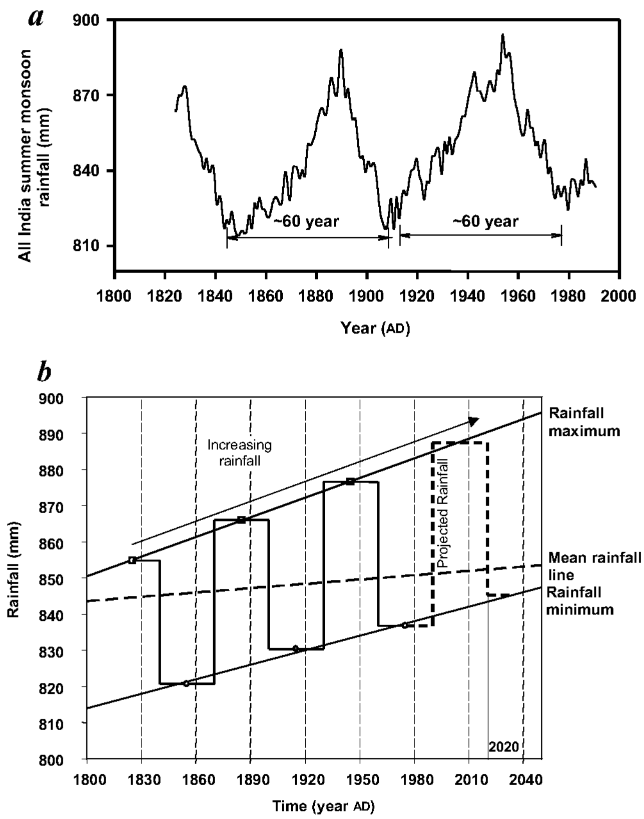

Figure 2. ***a***, Twenty-year running average of the Indian summer monsoon rainfall for the last 181 years, showing prominent ~60 year cycles, and ***b***, Variations in Indian monsoon rainfall in 30-year time-scale revealing increasing trends in rainfall maxima and minima.

contrast, and together with positive feedback processes like availability of moisture and atmospheric circulation might be significantly influencing intensity of Indian summer monsoon rainfall[15].

This ~60-year cycle (Figure 2 *a*) could be interpreted as tridecadal behaviour of the Indian monsoon, i.e. on an average, for about 30 years, we have good monsoon conditions and for the next 30 years, we experience relatively poor monsoon conditions. Indeed AISMR vs time plot show tricades of 'good' and 'poor' monsoon conditions (Figure 2 *b*). It can also be projected here that currently we are in good monsoon tricade and similar conditions will last till ~ AD 2020. Thereafter, for the next thirty years (from AD 2020 to 2050) relatively poor monsoon conditions are expected (Figure 2 *b*). It can also be seen from Figure 2 *b* that the overall monsoonal intensity (both maxima and minima of tricades) has increased in the last ~180 years. Whether this increase is a part of the longer solar cycle or whether it has contributions from global warming due to greenhouse effect or both, is crucial for developing predictive capability of monsoon. This is going to be quite challenging in the current anthropogenic era where numerous mutual interactions of greenhouse parameters are operating along with natural solar variability.

Corroboration from continental records

If the contention of solar forcing on SW monsoon intensity has to be taken seriously by the scientific community, it has to be corroborated with evidences from continental records. Several evidences have, indeed, been found recently, reinforcing this contention. For example, all solar minima during the mid Holocene (inferred from atmospheric ^{14}C fluctuations) were found to be coeval with reduced monsoonal intensity inferred from high resolution $\delta^{18}O$ of stalagmite (cave deposits) in the Oman region[16]. Supporting contention drawn from our marine record[15], a continental record from Nilgiri Hills (southern India) also registered a warmer and wetter phase relative to the present conditions, about 600 years ago coinciding with the MWP[21]. Reconstructed rainfall data using speleothem record of Gupteswar and Dandak caves of central India exhibit lower rainfall during LIA in central India relative to that during the MWP[22]. Thus, using high-resolution proxy data available from both marine as well as continental records, it can be suggested that intensity of Indian monsoon varies in unison with solar activity on the centennial timescale.

Response of other monsoon systems to solar forcing

To examine global impact of the short-term (multi-decadal) variations in solar activity, one has to concede how solar variability during the last millennium affected other monsoon systems. A warmer and drier climate during the MWP and a relatively cooler and wetter climate during the LIA have been reported in the east African monsoon system[11]. Severe drought periods coinciding with periods of high solar radiation with intervening epochs of increased precipitation during periods of low solar irradiation (during the Wolf, Spörer and Maunder minima) were experienced, which were interpreted in terms of lowering of water table in equatorial hydrological systems due to enhanced evaporation during increased solar activity[11]. However, studies from the Arabian Sea[10,15] show an increase in monsoon intensity during increased solar-activity periods. Figure 1 *d* shows the late level fluctuations in east African lake[11] during the last millennium, thus clearly demonstrating opposite behaviour of these (Indian and east African) monsoon systems. The most plausible mechanism for this contrasting behaviour could be that periods of increased solar activity cause more evaporation in the equatorial region, enhancing the net transport of moisture flux to the Indian subcontinent via SW monsoon winds, which eventually results in increased monsoonal precipitation[15]. Thus, miniscule increments in solar output may increase land–ocean thermal contrast responsible for onset of Indian monsoon coupled with higher evaporation in the east equatorial region supplying extra moisture to SW monsoonal winds and thereby providing a possible feedback process for intensification of Indian monsoon during periods of high solar activity. If this mechanism has been operating, small changes in solar activity in centennial timescale might have caused cool and dry conditions during the LIA (~ AD 1400 to 1750) and warm and moist conditions during the MWP (~ AD 1000 to 1400) on the Indian sub-continent. A similar solar variability caused an opposite scenario, i.e. cool and wet conditions during the LIA and dry and hot conditions during the MWP in the eastern equatorial region.

Bond *et al.*[14] recently reported influence of solar activity on surface hydrographic conditions of North Atlantic during the Holocene. They observed cooler episodes associated with increased ice drift in the north Atlantic region coeval with reduced monsoonal intensity of SW monsoon (inferred from stalagmite record of the Oman region[13]) during the entire Holocene. This study brings out a close link between high-latitude climate and monsoonal climate in centennial timescale also, which is not surprising as teleconnections between these two different climatic regimes in longer (glacial–interglacial) timescales have been reported earlier.

$\delta^{13}C$ of peat (a proxy for humidity or precipitation) record from northeastern China (42°20′N, 126°22′E), reveals significant climatic shifts and eight severe droughts during the last 6000 years, coinciding with solar maxima[12]. Inferred precipitation record of Chinese monsoon shows many of the solar periodicities. Important to the present context, the last 1200 years of isotopic record of peat from this region reveals a wet and cold climate during the LIA relative to the MWP, similar to conditions in the equatorial east African region[11]. Such climatic manifestations, i.e. cool and wet climate during the LIA relative to the MWP have also been inferred in Europe[23]. Inferred palaeo-hydrological records using palaeo-lake salinity of Moon Lake in Northern Great Plains (NGP) of North America revealed frequent drought conditions during several parts of the MWP, while relatively moist (wetter) conditions were found to have occurred during the LIA[23]. Though it appears that different climatic regimes have different responses to solar variability in multi-decadal timescale, an important point to note here is that solar variability, indeed, plays an important role in governing major hydrological systems, especially the Indian monsoon.

Conclusion

A comparative study of the Indian monsoonal system in conjunction with other rainfall systems reveals an important point, i.e. all the above-mentioned regional precipitation systems resonate with short-term (multi-decadal) solar frequencies; but the net result in terms of total amount of rainfall maybe different at different locales depending on their regional geographic conditions. The Indian subcontinent appears to be warmer and wetter with increase in solar radiation, while most of the other regions around the globe experience warmer and drier climate under similar conditions, most probably due to net influence of solar radiation on regional P–E balance. Nonetheless, these comparisons bring out an important conclusion, i.e. solar variability on centennial timescale is able to produce diverse responses in regional hydrology, which has to be taken into account while modelling future rainfall patterns over large geographical areas.

So far, solar forcing has been treated as a positive feedback in the total radiative forcing comprising greenhouse gases[24]. If solar forcing has such a direct and significant impact on the intensity of the Indian monsoon, it must also influence other important parameters governing net rainfall; for example, total cloud cover, atmospheric dust, etc. which reduce direct input of solar radiation on the earth and, in turn, causes an ultimate cooling effect. Therefore, it is recommended that solar influence on regional hydrological regimes has to be studied in more detail and should be taken into account while assessing total radiative forcing of the current climate in the anthropogenic era in which large uncertainties are involved due to existence of several mutually interactive parameters.

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ACKNOWLEDGEMENTS. We thank Profs. B. L. K. Somayajulu and S. Krishnaswami, Physical Research Laboratory (PRL), Ahmedabad for his suggestions and critical comments. Constructive comments from Ravi Bhushan, PRL, Ahmedabad also proved helpful in the preparation of this manuscript. R.A. thanks Dr P. C. Pandey, Director and Dr N. Khare, NCAOR for extending facilities and help during the preparation of this manuscript.

Received 5 March 2003; revised accepted 2 June 2003

MEETINGS/SYMPOSIA/SEMINARS

INAE Conference on Nanotechnology (ICON-2003)

Date: 22–23 December 2003
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Topics include: Assessing the current trends in the production and use of botanical pesticides, Integrating traditional practices for insect pest management, Evaluating the usefulness of microbial pesticides, Reviewing the role of biotechnology for green pesticides production and use, Understanding the impact of use of pheromones.

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