

Impact of solar variability on the low frequency variability of the Indian summer monsoon

J.R KULKARNI, M. MUJUMDAR, S.P. GHARGE, V. SATYAN and G.B. PANT

Indian Institute of Tropical Meteorology,

Pune - 411008, India

सार - अखिल भारतीय ग्रीष्मकालीन मानसून वर्षा (ए.आई.एस.एम.आर.) में घटबढ़ के आवधिक व्यवहार पर पहले 60 - 70 वर्षों तक की गई जाँच से वर्षा की कम आवृत्ति की प्रवृत्ति (एल.एफ.एम.) का पता चला है। सौर विकिरण में परिवर्तन इस परिवर्तनशीलता का एक संभावित स्रोत हो सकता है। इसका पता लगाने के लिए 1871 से 1998 तक के 128 वर्षों के काल-खंडों के सौर विकिरण के आँकड़ों की जाँच की गई है। इन काल-खंडों से कम आवृत्ति प्रवृत्ति का पता लगाने के लिए तरंगिका रूपान्तर (डब्ल्यू.टी.) पद्धति का अनुप्रयोग किया गया है जो इसके बहुत अनुरूप पाई गई है। अखिल भारतीय ग्रीष्मकालीन मानसून वर्षा (ए.आई.एस.एम.आर.) की सौर विकिरण के प्रति संवेदनशीलता का पता लगाने के लिए पूरे मामले का विस्तार से अध्ययन किया गया है। महासागर - थल - वायुमंडल केन्द्र (सी.ओ.एल.ए.) के सामान्य परिसंचरण निदर्श (जी.सी.एम.) को 1986 की ग्रीष्मकालीन मानसून ऋतु के लिए कंट्रोल रन (सौर स्थिर के जलवायविक मान अर्थात् 1365 Wm^{-2} का प्रयोग करते हुए) और शोधित आयनिक सौर स्थिर स्थिति (10 Wm^{-2} तक शोधित) में समाकलित किया गया है। इस अध्ययन से पता चलता है कि विस्तारित और स्थिर सौर परिदृश्य में भारतीय क्षेत्र में विस्तृत पैमाने पर वायुमंडलीय परिसंचरण मानसून की अच्छी वर्षा के लिए अनुकूल है। एल.एफ.एम. में ए.आई.एस.एम.आर. पर सौर विकिरण के प्रभाव का अध्ययन करने के लिए संकल्पनात्मक निदर्श का भी सुझाव दिया गया है।

ABSTRACT. Earlier investigations into the epochal behaviour of fluctuations in All India Summer Monsoon Rainfall (AISMR) have indicated the existence of a Low Frequency Mode (LFM) in the 60-70 years range. One of the probable sources of this variability may be due to changes in solar irradiance. To investigate this, time series of 128-year solar irradiance data from 1871-1998 has been examined. The Wavelet Transform (WT) method is applied to extract the LFM from these time series, which show a very good correspondence. A case study has been carried out to test the sensitivity of AISMR to solar irradiance. The General Circulation Model (GCM) of the Center for Ocean-Land-Atmosphere (COLA) has been integrated in the control run (using the climatological value of solar constant *i.e.* 1365 Wm^{-2}) and in the enhanced solar constant condition (enhanced by 10 Wm^{-2}) for summer monsoon season of 1986. The study shows that the large scale atmospheric circulation over the Indian region, in the enhanced solar constant scenario is favourable to good monsoon activity. A conceptual model for the impact of solar irradiance on the AISMR at LFM is also suggested.

Key words - Monsoon variability, Low frequency variability, Solar variability, GCM study, Wavelet transform.

1. Introduction

All India Summer Monsoon Rainfall (AISMR) exhibits variability on the scales ranging from subsynoptic to climatic scales. The intraseasonal and interannual variabilities of AISMR have been extensively studied for variety of scientific and practical applications. However the enhanced interest in Low Frequency Variability (LFM) of AISMR is in concurrence with recent interest in the long-term climate change studies. Joseph (1976), using AISMR data for the period 1891 to 1974, showed the

existence of LFM in AISMR. The ~ 60-year period-wave was described in terms of epochal behaviour of AISMR. He identified three epochs *viz.* epoch A: 1891-1920, epoch B: 1930-1960, and epoch C: 1965-1974. The epochs A and C were characterized by many years of monsoon failures leading to severe droughts while epoch B was characterized by less number of monsoon failures. Mooley and Parthasarathy (1984) have applied 10-year moving averages on 108 years (1871-1978) AISMR data and ascertained the statistical significance (at 5% level) of the epochs. Verma *et al.* (1985) studied the decadal variability

over the period 1881-1980. The study revealed the existence of three/four contiguous decades of above normal AISMR activity followed by the three/four contiguous decades of below normal AISMR activity, which substantiated the LFM identified by Joseph (1976) and Mooley and Parthasarathy (1984). They further showed that the decadal variability in AISMR was significantly related to decadal variability of Northern hemispheric mean surface air temperature at 5% level of significance. Pant *et al.* (1988) extensively studied the LFM in AISMR using smoothing method of cubic spline to AISMR time series and other global and regional parameters. They demonstrated that the LFM was not only limited to seasonal monsoon rainfall, but also found in the various monsoon related parameters such as (1) monsoon onset dates over Kerala, (2) storms and depressions in Bay of Bengal and Arabian Sea during monsoon, and (3) number of break-monsoon days in July and August. The epochal behaviour was also noticed in the associations of AISMR with some of the global parameters (Krishnakumar *et al.* 1995).

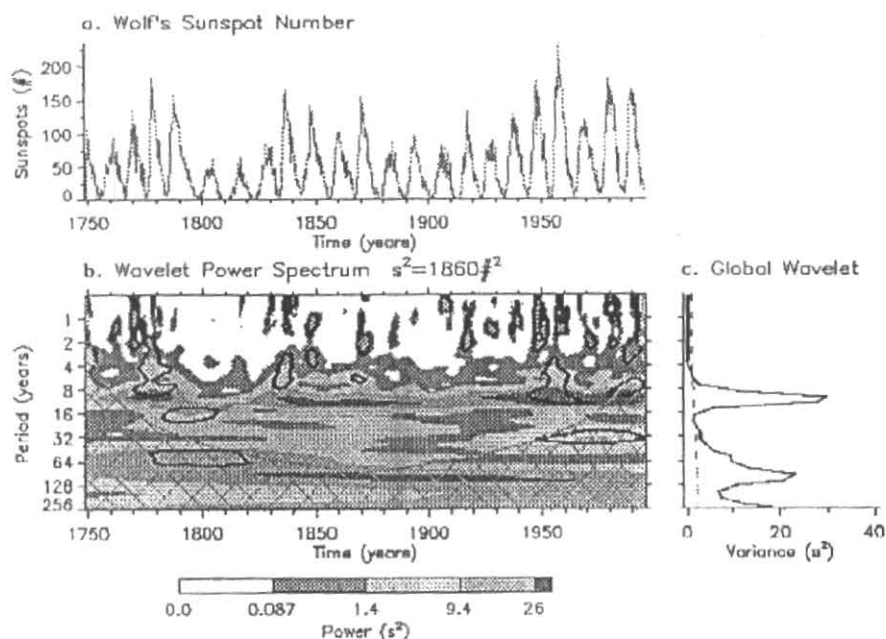
In the recent years there has been a major revival of interest in AISMR-LFM which has formed the major objective of the intensive global observational, analysis and modelling programmes such as CLIVAR. Temporal changes in the observed association between ENSO and AISMR have also provided incentive for study of LFM. In the last 8 years of the present decade, there was a prolonged ENSO from 1991-94, and ENSO like conditions in the year 1997, however the AISMR activity remained normal during these years. One of the explanations offered to this apparent de-association between AISMR and ENSO was based on the epochal behaviour of AISMR. Kripalani and Kulkarni (1997) analysed 125-year (1871-1996) of AISMR data using Cramer's t-statistic for 11-year running means. They showed that the impact of El-Nino (La Nina) on the AISMR was more severe during the below (above) normal epochs. They further showed that the AISMR had entered into above normal epoch in the year 1990, which might have caused to lessen the impact of ENSO in the present decade. This study has shown that the LFM is indeed important in modulating the performance of AISMR on the interannual scale also.

As oceans have a long memory and enormous heat capacity, the long term oceanic variability on the scale of LFM has been speculated as the underlying mechanism for AISMR-LFM. However not many studies are carried out to establish the relation between the two. Bhalme *et al.* (1997) examined SSTs of northern and southern hemispheric oceans for the 120-year (1871-1990) period. They defined an index based on the

southern hemispheric SSTs. They showed that the two epochs found by Joseph (1976) *viz.* A and C having frequent occurrences of droughts broadly coincided with the warm anomalies of southern hemispheric SSTs. It is well known fact that the SSTs over equatorial Pacific Ocean have profound influence on the interannual variability of AISMR. Gu and Philander (1995) observed the existence of the LFM in the SST variability of equatorial west Pacific Ocean. Sikka (1980) pointed out that the epochs of differing frequencies of monsoon droughts corresponded to the epochs of differing frequencies of the El Nino.

As yet, here is no clear understanding regarding the exact source for the LFM in the oceanic surface temperature variability. Some of the probable sources considered are: (1) changes in deep-water formation and global thermohaline circulation, (2) climatic fluctuations arising from the strong nonlinearity of the climate system, (3) stochastic fluctuations and (4) solar variability. Reid (1987) showed that the globally 11-year-averaged SSTs varied in phase with ~80 year cycle of the solar activity. Reid (1991) further showed that, this in-phase relationship was also found in the surface temperature variations in all the three major oceans. Therefore it was argued that the LFM in SSTs was more likely due to solar forcing rather than due to other sources described above. This formed the basis for looking for the source of AISMR-LFM in the LFM of solar variability. Mehta and Lau (1997), using the low-pass filtered (longer than 24 years) time series of solar irradiance and AISMR, showed the existence of the relationship between the two. They also showed the out of phase relationship between solar irradiance and equatorial central-east Pacific SSTs, at the scale of LFM. They put the following hypothesis for the monsoon-solar irradiance relationship.

The seasonal reversal of the monsoon winds over India is controlled by the seasonal reversal of the land-ocean heating gradient. Since the Indian subcontinental land mass (including the Tibetan plateau) has much smaller heat capacity than the Indian Ocean, the Arabian Sea, and the Bay of Bengal, the temperature of the land mass would increase/decrease almost simultaneously with increasing/decreasing solar irradiance. Although the amplitude of the multidecadal solar irradiance variability is small, a positive anomaly would bias the solar irradiance incident on the monsoon region towards larger values for 20-30 years. A long-lived, above-normal irradiance anomaly would strengthen the land-ocean-heating gradient and, in turn the monsoon winds. An increase in evaporation and/or an above normal moisture flux might result in above-normal rainfall over India.



Figs. 1(a-c). (a) Time series of sunspots (from Nat. Geophys. Data Center). Wolf's sunspot number since 1750 A. D. (b) Wavelet power spectrum. The power has been scaled by the time series variance (s^2); counter levels are chosen so that 75%, 50%, 25% of the wavelet power is above each level, respectively. Black counter is the 10% significance level, using the global wavelet spectrum as background and (c) The global wavelet power spectrum. The dashed line is the 10% significance level for the global wavelet spectrum, assuming a white-noise background (Taken from Torrence and Compo 1999)

In this paper, an attempt is made to examine further the relationship between the solar irradiance and AISMR. Mehata and Lau (1997) have used low-pass-filtered (with the period 24-years) time series. In addition to LFM, the solar irradiance has a large power in the modes with periods 46, and 51 years. We have used Wavelet Transform (WT) to extract the variability exclusively corresponding to ~64 year period which provided better relationship between the two. Further we tested the above-referred hypothesis using the General-Circulation Model (GCM). A sensitivity experiment was carried out to test the impact of change in the solar irradiance on the large-scale atmospheric circulation over India during the monsoon season using COLA GCM. The objective of the GCM study was to examine whether the atmospheric circulation in the enhanced solar irradiance scenario is conducive to good monsoon activity.

2. Solar and AISMR covariability

2.1. Previous studies with the sunspot numbers

The Sun's output varies on an enormous range of time scales from minutes in the case of flares, to the

billion-year time scale of solar evolution. The variations are measured by different indices such as magnetic activity, prominences, faculae, and number of sunspots. The most of these indices correlate very well with the sunspot numbers. Due to the availability of long records of sunspot numbers, the solar variability studies have been carried out mainly using the sunspot numbers. The analysis of sunspot numbers has shown the existence of modes with period 5.5, 10-12, 22-23, 40-50, 80-90 years (Lamb, 1972, Herman and Goldberg 1985).

Several studies in the past have been carried out to correlate the sunspots with the monsoon activity. Walker (1915) showed that the correlation coefficient (CC) of sunspots with total rainfall over the plains of India, as given by all the stations in existence from 1865 - 1912 was 0.26. He further showed that the solar activity affected the monsoon as a whole, but not the irregularities in the geographical distribution of the rainfall of India. Jagannathan and Bhalme (1973) found that the mean rainfall was larger during sunspot maximum than that in sunspot minimum over north India and the central parts of peninsula. Over the rest of the country, the rainfall during the sunspot minimum is larger than that during the sunspot

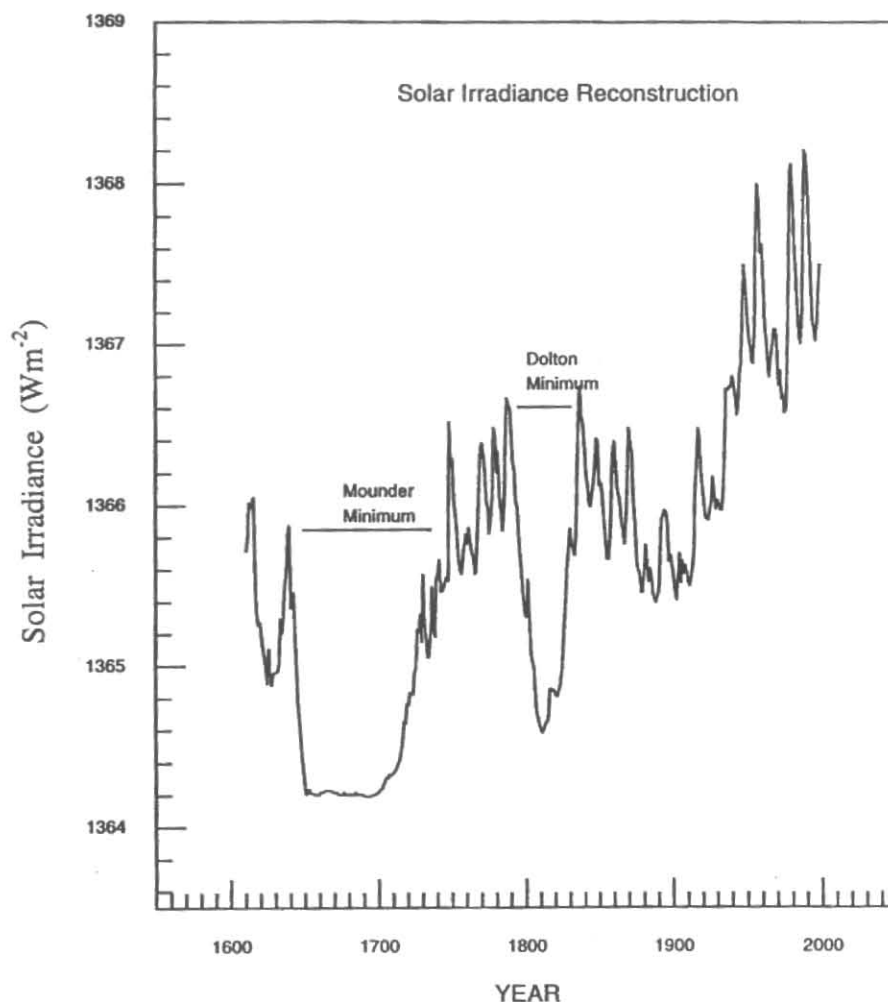


Fig. 2. Reconstructed solar irradiance (Wm^{-2}) at the top of the atmosphere from 1610 to the present (data from Lean *et al.* 1995)

maximum. Bhalme and Mooley (1981) provided evidence of an approximately 22-year cycle in the fluctuations of flood area indices over India for the 89-year period 1891-1979, showing strong coherence with the double (Hale) sunspot cycle. Furthermore, they were able to demonstrate the consistent occurrence of large-scale flood events in the major sunspot cycle by harmonic dial analysis. Ananthkrishnan and Parthasarathy (1984) found significant excess rainfall years around the peak phase of alternate sunspot cycles. Bhalme and Jadhav (1984) showed the strong tendency for occurrence of floods in the positive (major) sunspot cycle than in the negative (minor) sunspot cycle. They further suggested that large-scale flood recurrence over India was in some manner controlled by long-term solar activity.

2.2. Evidence for LFM in solar variability

The above referred studies examined the relationship on the scales extending up to ~22-year period. One of the scales in the sunspot spectrum longer than ~22-year period and of interest to us is around 70 years. The variability on this scale has been found in many solar-terrestrial physics phenomena. Gilliland (1981,1982) found the variations of solar radius with the time scale of ~80-year. Johnsen (1970) analyzed the ice accumulation during the last 800-year period. He found two peaks corresponding to climatic oscillations with periods of 78 and 181 years. Feynman and Fougere (1984) observed that the MEM analysis of number of aurora in Europe from A.D. 450-1450 showed strong stable peak at period 88.4-year. Fig. 1(a) shows

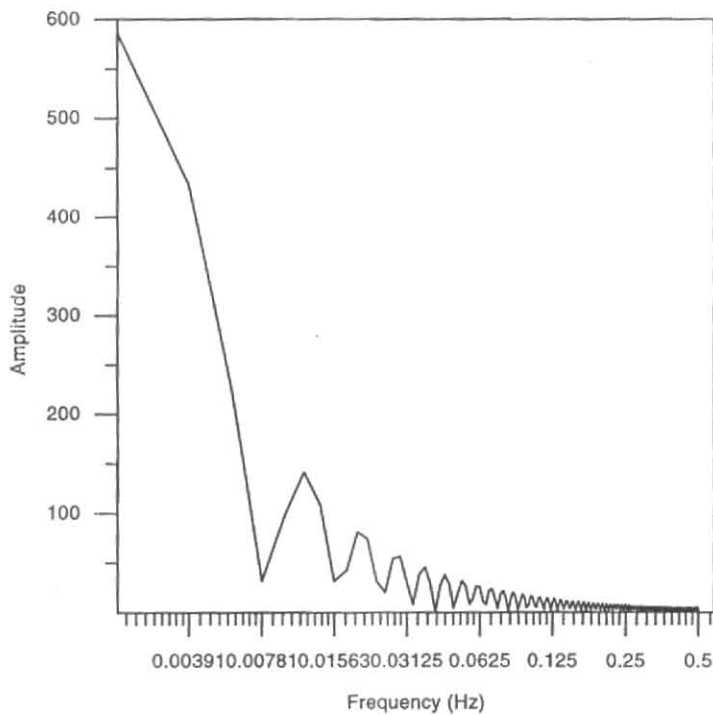
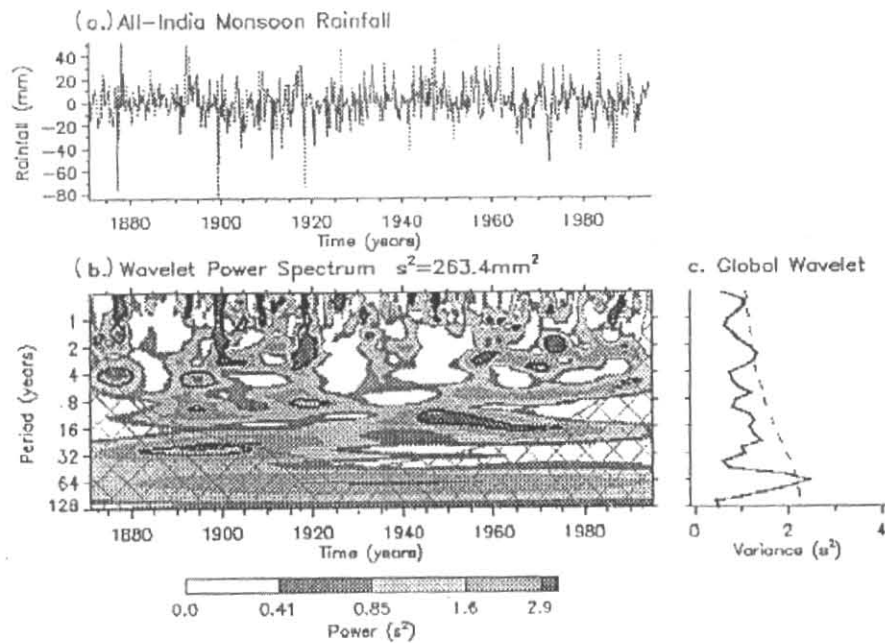


Fig. 3. Fast Fourier Transform of solar irradiance time series



Figs. 4(a-c). (a) Time series of AISMR (deviation from normal in mm), (b) Wavelet power spectrum. The power has been scaled by the time series variance (s^2); counter levels are chosen so that 75%, 50%, 25% of the wavelet power is above each level, respectively. Black counter is the 10% significance level, using the global wavelet spectrum as background and (c) The global wavelet power spectrum. The dashed line is the 10% significance level for the global wavelet spectrum, assuming a white-noise background (Taken from Torrence and Compo 1999)

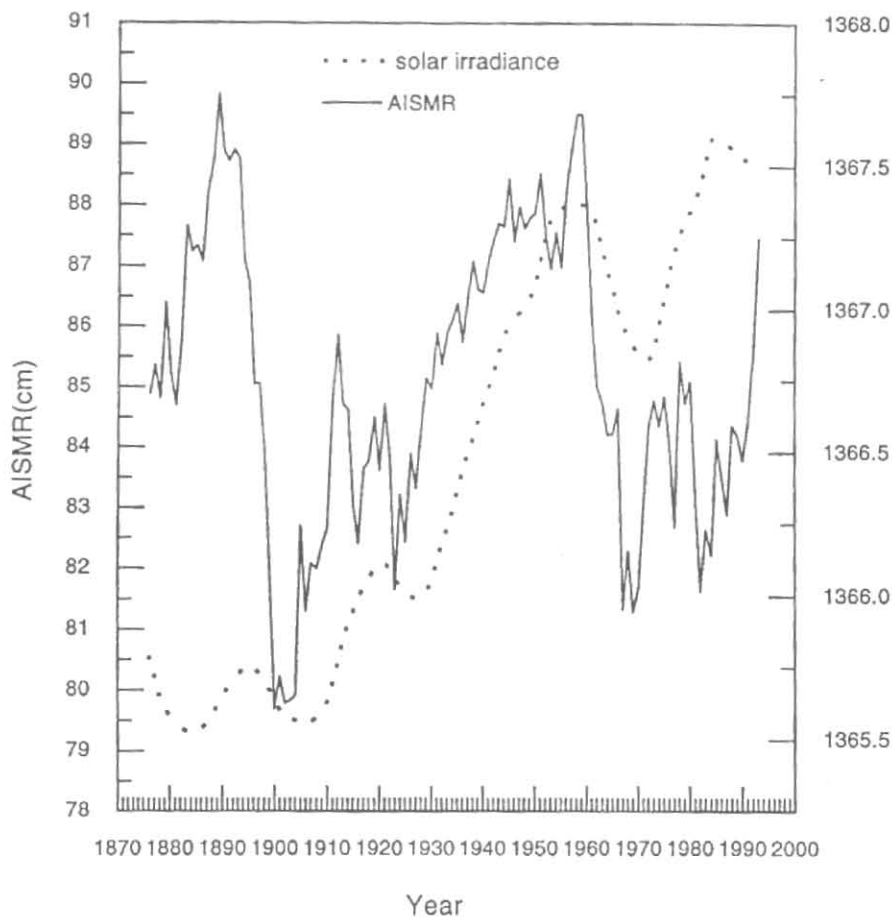


Fig. 5. Eleven-year running means of solar irradiance (Wm^{-2}) (right axis) and AISMR (cm) (left axis) time series

Wolf's sunspot numbers since 1750 A. D. The power spectrum in the Fig. 1(c) shows the existence of LFM in the sunspot number time series (Torrence and Compo 1999).

Since 1850, industrially produced concentrations of green house gases CO_2 , CH_4 , N_2O , CFC_s and tropospheric sulphate aerosols have increased (Houghton *et al.* 1995). The overall activity level of the sun has risen too (NRC 1994). Many fairly simple numerical models of terrestrial climate have been developed in recent years in order to estimate the relative importance of CO_2 solar and volcanic forcing. Gilliland and Schneider (1984) simulated the climate of past century using box climate model. They found that the variances accounted by these three forcings in the simulated mean surface temperature were 32%, 11% and 38% respectively. Kelly and Wigley (1992) used energy balance model to simulate the effects of greenhouse and solar forcings over the period 1765-1985. These studies incorporated solar forcing on the scale of

LFM in the solar irradiance. Their study revealed that this forcing combination could explain many features of the surface temperature variability. These studies clearly bring out the existence of LFM in the solar variability.

2.3. Empirical study between AISMR and solar variability at LFM

Joseph (1976) suggested the empirical relation between AISMR and solar activity on the low frequency scale. He showed that the monsoon epochs A and C were the epochs having low sunspot activity and epoch B was the epoch of high sunspot activity. Recently Lean *et al.* (1995) reconstructed solar irradiance data at the top of the atmosphere, making use of sunspot numbers and information about solar faculae since 1600 A.D. (Fig. 2). The series has mean 1365.64 Wm^{-2} and standard deviation 0.97 Wm^{-2} . The two epochs of no sunspot activity corresponding to Mounder minimum and Dalton minimum are clearly seen from the figure. It further shows the

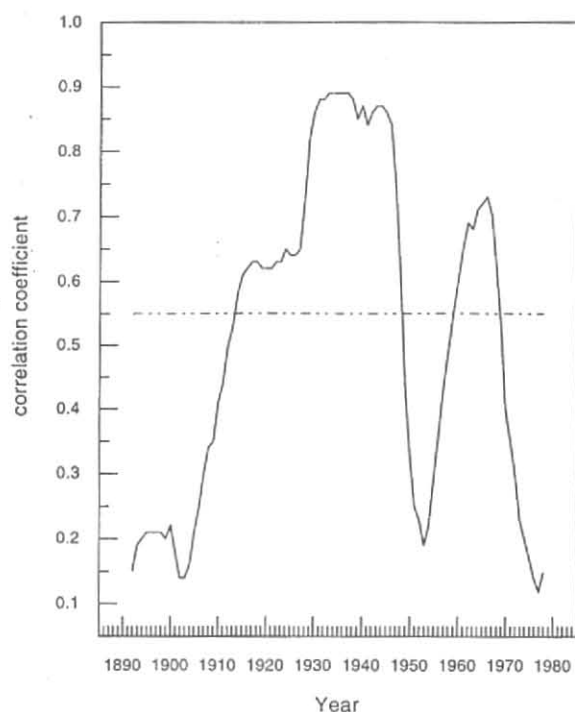


Fig. 6. Correlation between 11-year-averaged solar irradiance and AISMR time series computed in 31-year running window. The horizontal line is for 1% level of significance

increasing trend in the solar irradiance from 1810 onwards to date. The solar irradiance increased from 1364.6 Wm^{-2} in the year 1810 to 1368.2 Wm^{-2} in the year 1989. Thus there is a net increase of 3.6 Wm^{-2} in the last ~200 years. The correlation of reconstructed solar irradiance and northern hemispheric surface temperature is 0.86 in the pre-industrial period from 1610-1800, implying a predominant solar influence. Extending this correlation to the present suggests that solar forcing may have contributed about half of observed 0.55°C surface warming since 1860 (Lean *et al.* 1995). Fig. 3 depicts the Fast Fourier Transform (FFT) of the series. The figure reveals LFM along with other prominent periods *viz.* 256.0, 170.7, 102.0, 51.2, 46.5, 24.4, 12.2, 8.1, 6.1, and around 2 years.

The 11-year time averaging is applied to the solar irradiance and AISMR data for the period 1871-1998. The data for AISMR has been taken from Parthasarathy *et al.* (1992) up to 1991 and updated up to 1998. The time series has mean 85.14 cm and standard deviation 8.4 cm. Fig. 4(a) shows AISMR time series and 4(c) shows the power spectrum of it. It can be seen that a significant power resides in the LFM. The standard deviations of smoothed series of solar irradiance and AISMR are 0.73 Wm^{-2} and 2.4 cm respectively. The variances retained in the

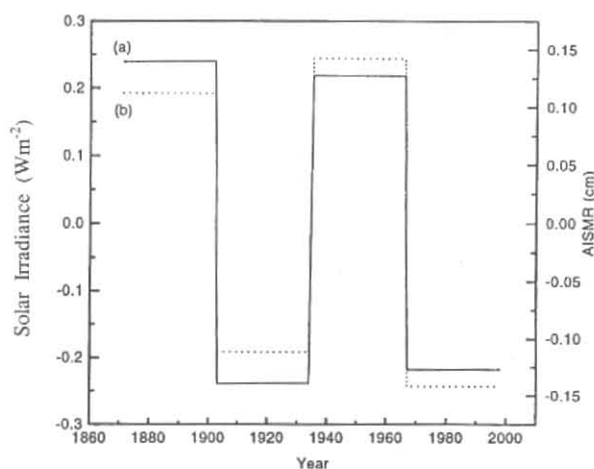
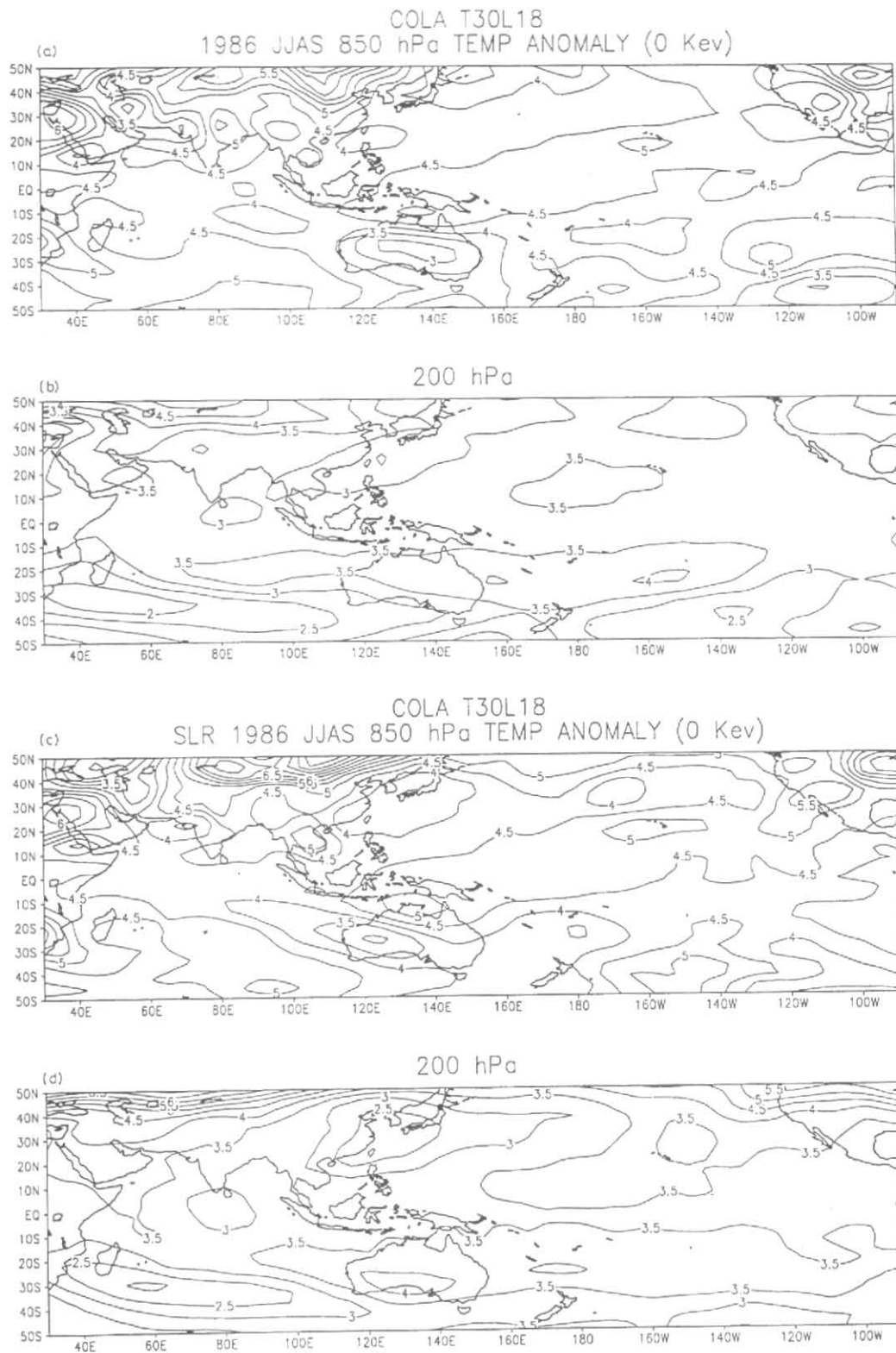


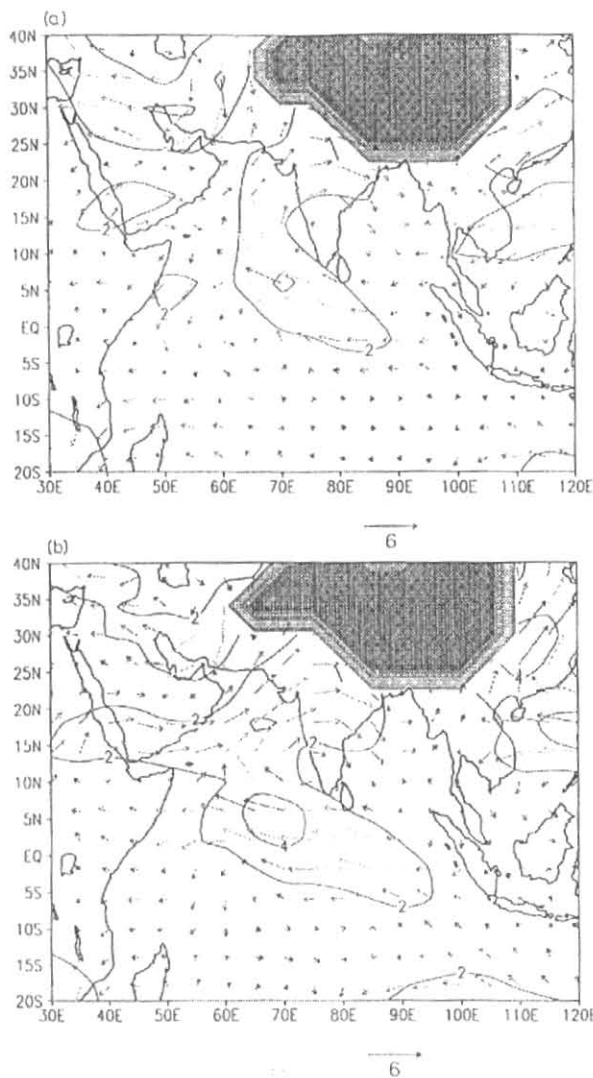
Fig. 7. Reconstructed 64-year mode in solar irradiance (a) and AISMR (b)

smoothed solar irradiance and AISMR time series are 56.6% and 8.2% respectively. Fig. 5 shows the plots of 11-year-averaged AISMR and solar irradiance. The most remarkable similarity in the two figures is observed over the period 1910-1980. Fig. 6 shows the correlation in the two series computed for 31-year running window. The correlation is significant at 1% level during the period 1915-1948 and 1955-1968. The 11-year averaging retains only the LFM in AISMR but retains additional modes of period ~24, ~40-50 years in the solar irradiance variability which may be the reason for lack of agreement over the entire record.

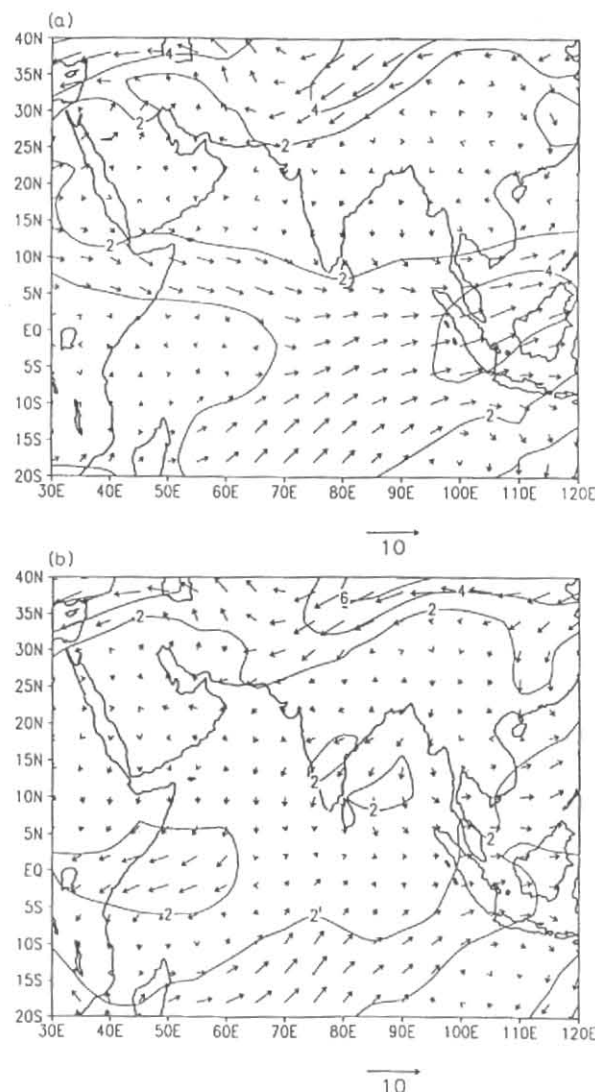
For removing these modes from the solar irradiance time series, it is required to average the time series for more than 24-year period. This will reduce the length of the series drastically. Hence a modern technique of WT has been applied to extract the variability corresponding to LFM from both the series. The concept of WT was introduced in early 1980's in a series of papers by Morlet *et al.* (1982a,b), Grossmann and Morlet (1984). Since it's formalism and some significant work by Daubechies (1988, 1992), and Chui (1992), WT has emerged as a powerful tool for analysing localized variations of power within the non-stationary time series. Torrence and Compo (1998) have provided all essential details necessary for wavelet analysis. Figs. 1(b) and 4(b) show the wavelet power spectra of sunspot numbers and AISMR time series using continuous Morlet function (Torrence and Compo 1999). The activity of LFM is seen to be present throughout the period in both the series. The discrete WT has an advantage that it is better localised in the frequency domain. The discrete Haar WT is applied to decompose the time series of AISMR and solar irradiance into 7 dyadic scales with periods 2, 4, 8, 16, 32, 64, and 128



Figs. 8(a-d). (a) COLA GCM simulated 850 hPa temperature anomalies (from model climatology) in the climatological SC run of season 1986, (b) same as (a) but for 200 hPa. (c) same as (a) but for the enhanced solar constant scenario, and (d) same as (b) but for the enhanced solar constant scenario



Figs. 9(a&b). (a) COLA GCM simulated 850 hPa wind anomalies (from model climatology) in the climatological SC run of monsoon season 1986, and (b) same as (a) but for enhanced Solar constant scenario

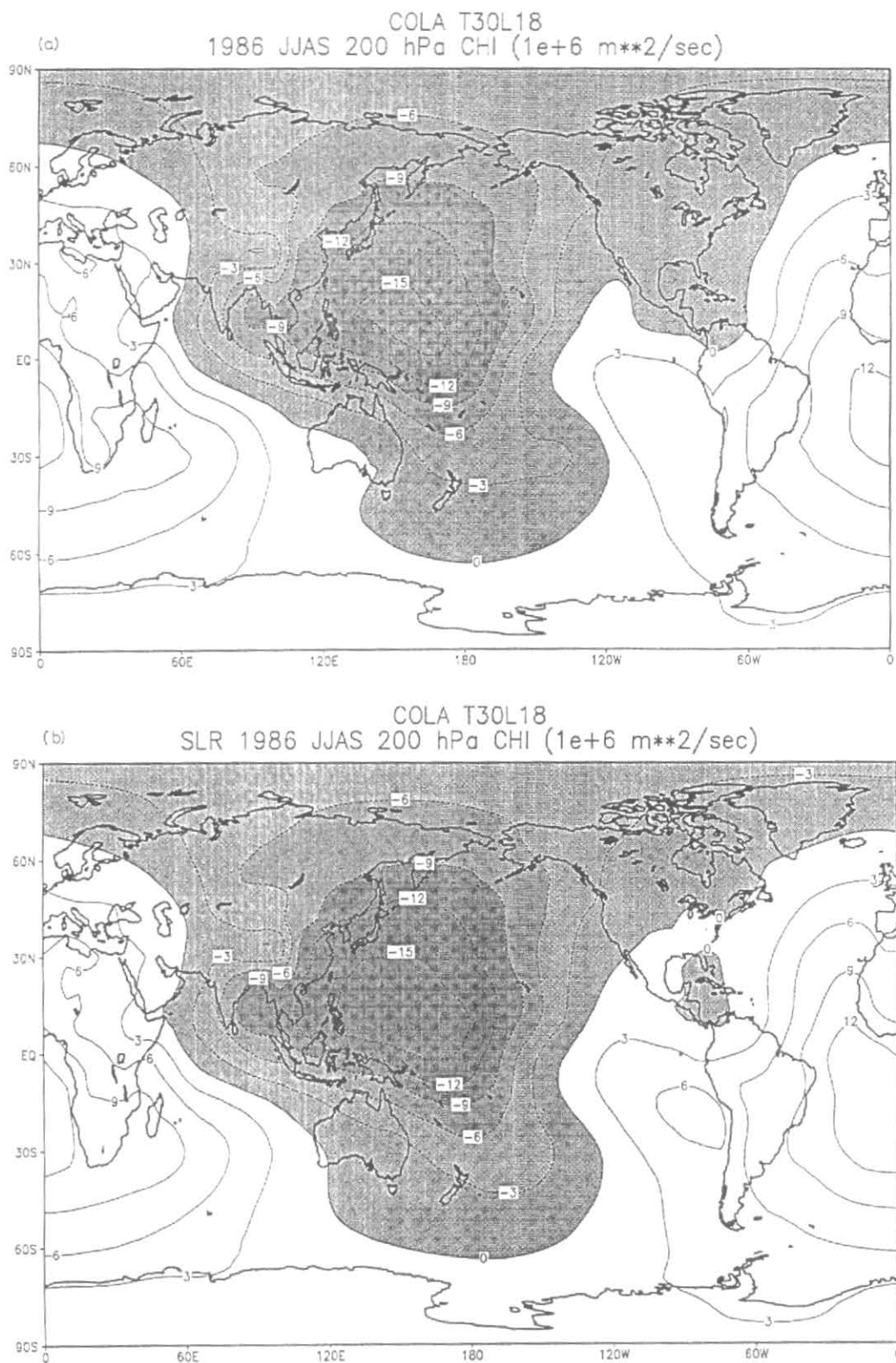


Figs. 10 (a&b). (a) COLA GCM simulated 200 hPa wind anomalies (from model climatology) in the climatological SC run of monsoon season 1986 and (b) same as (a) but for enhanced Solar constant scenario

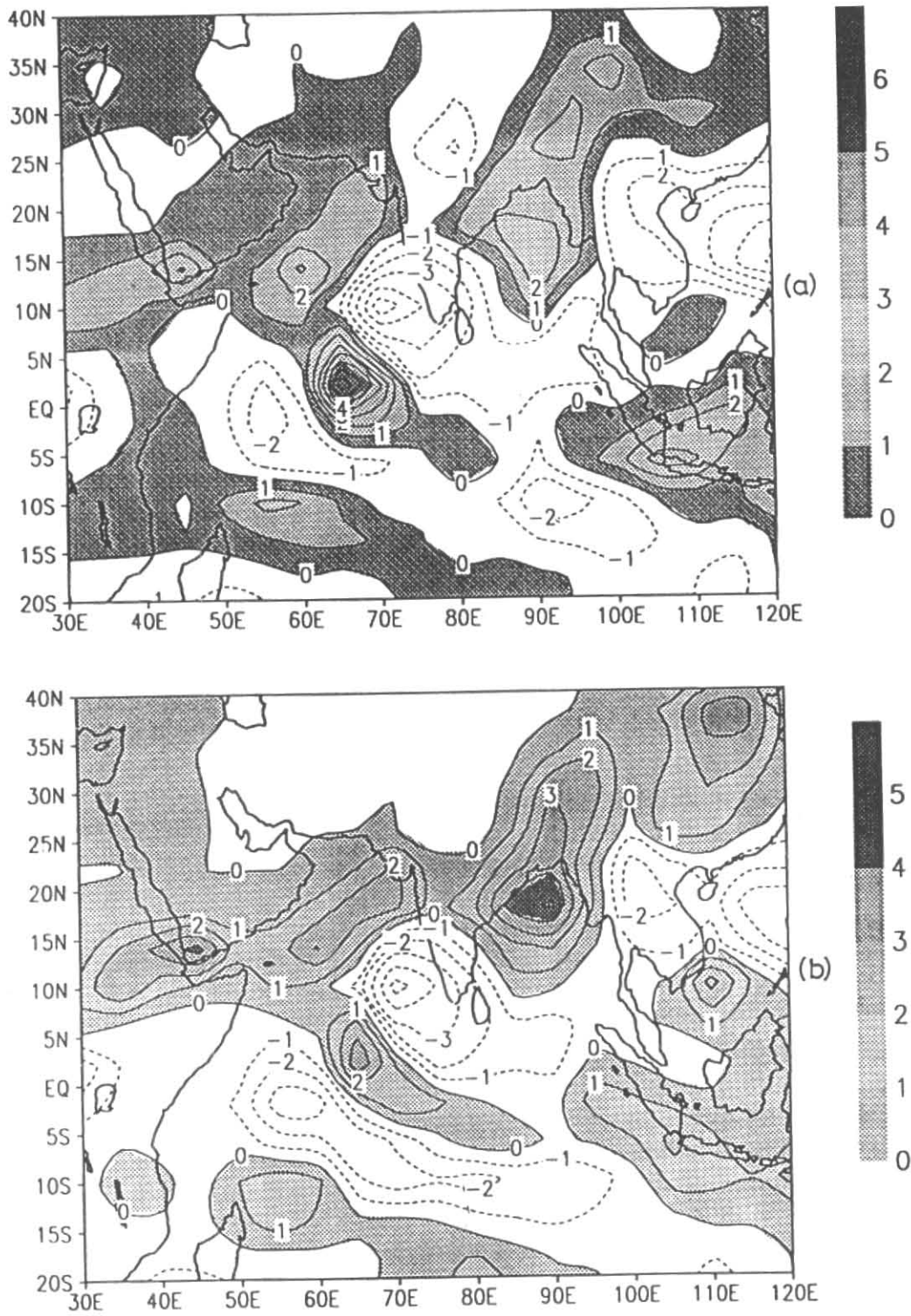
years. The time series corresponding to 64-year period mode was reconstructed. The method of computation and other details of the Haar WT are given in Kulkarni *et al.* (1999), and Kulkarni (2000). Fig. 7 shows the LFM signal in the solar irradiance and AISMR. The variance accounted by these further smoothed series reduces to 4% and 9% in AISMR and solar variability respectively. The nonstationary character of LFM is clearly observed in both the series. The AISMR-LFM in the second half period is slightly more active (having larger amplitude), whereas reverse is observed in the case of solar irradiance. The most important feature observed is the very close relationship between the two.

3. GCM sensitivity experiments

Numerical simulations of the impact of solar variability on climate fall into four categories. Category first comprises of GCM experiments, confined mostly to the lower atmosphere, in which enhanced solar activity is represented by changes in spectrally integrated solar constant (SC). The second category consists of the GCM studies of the dynamical response of the middle atmosphere to changes in solar ultraviolet. These two categories do not include interactive photochemistry. The third category consists of studies with the photochemical response of middle atmosphere to enhanced solar



Figs. 11(a&b). (a) COLA GCM simulated 200 hPa divergence anomalies (from model climatology) in the climatological SC run of monsoon season 1986 and (b) same as (a) but for enhanced Solar constant scenario



Figs. 12(a&b). (a) COLA GCM simulated seasonal rainfall anomalies (from model climatology) in the climatological SC run of monsoon season 1986, (b) same as (a) but for enhanced Solar constant scenario

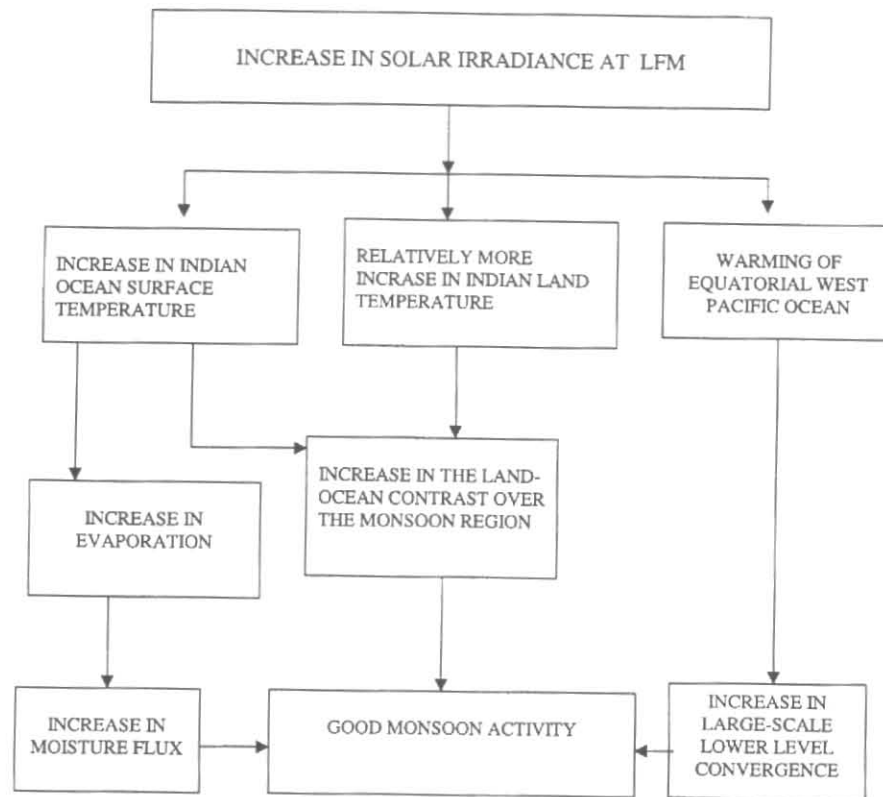


Fig. 13. The suggested mechanism of impact of LFM-solar irradiance on LFM-AISM

ultraviolet. The fourth category, which is still in infancy, attempts to represent solar variability by realistic changes in both irradiance and ozone concentrations (Haigh 1999). Here we focus our study on the category first *i.e.* the impact of changes in spectrally integrated SC.

Wetherald and Manabe(1975) used simplified GCM with a swamp ocean and ice-albedo feedback. They observed that the response of the tropospheric zonal mean temperature to a 2% increase in the SC was very similar to that which they calculated for a doubling of the concentration of CO₂. The greatest warming was found in the tropical upper troposphere where moist convection dominates. They further observed a cooling in the tropical lower stratosphere associated with an increase in tropopause height due to enhanced tropical convection. Later GCM studies of the impact of changes in SC have revealed similar responses in the cooling of lower stratosphere and increase in tropical convection (Cubash *et al.* 1997; Nesme-Ribes *et al.* 1993; Sadourney 1994; Royer *et al.* 1994). Goddard Institute for Space Studies

(GISS) GCM estimates a global surface temperature decrease by 0.47°C for 0.25% decrease in solar irradiance (Rind and Overpeck 1993). But observed cooling was non-uniform over the globe. The continental areas along 40° N were cooler by 1°C. Equilibrium simulations of climate response to changing solar radiation using Laboratory de Meteorologie Dynamique (LMD) atmospheric GCM estimated surface temperature reductions of 1.5°C for a 0.4% irradiance decrease.

In the present study, we have used, COLA GCM with triangular truncation at wave number 30. The vertical structure in the model is represented by 18 unevenly spaced levels using sigma coordinate system. The model is based on a modified version of NMC global spectral model used for medium-range weather forecasting. The formulation of the model is given in Sela (1980) and modified version in Kinter *et al.* (1988). Gadgil and Sajani (1998) compared the monsoon simulation by all the GCMs and classified them into A, B, and C categories, A being the best. The COLA GCM falls into category A2.

To test the hypothesis put forward by Mehta and Lau (1997), we have carried out a case study using COLA GCM. The impact of increase in the solar radiation on AISMR occurs mainly through two ways: (1) direct increase in the land-ocean gradient, and (2) increase in the SSTs in such a way as to favour the monsoon circulation (*i.e.* increase in the equatorial west Pacific SSTs). In the case study, we have integrated the COLA model for monsoon season of 1986. The year 1986 was a weak monsoon year with summer monsoon rainfall 74.6 cm about 12 cm below normal. The equatorial central and east Pacific SSTs were above normal. Kripalani and Kulkarni (1997) showed that the impact of El Nino is reduced in the above normal epoch of AISMR. The selection of the year is done to test this another hypothesis. In real conditions the increase in the solar irradiance at LFM is about 0.25%. In order to take into account the impact of enhanced SC on AISMR, through SSTs, we have taken the value of increased SC by 10 Wm^{-2} ($\sim 0.75\%$). The atmospheric initial conditions were of 1 May 1986. Figs. 8(a-d) show the anomalies in the temperature distribution in the control and enhanced SC run. The anomalies are estimated with respect to model climatology. The SSTs over the central-east Pacific in this year were above normal, consequently there was an eastward shift in the oceanic convective zone. The positive anomalies of 3.5°C over the central Pacific Ocean (Fig. 8b) are indicative of the observed eastward shift in the convective zone. It is seen that there is an increase of temperature especially over the land region, at 850 hPa (Fig. 8c) and 200 hPa (Fig. 8d) in the enhanced SC experiment, predominantly at 40°N latitude. The results are in good agreement with those of Hansen *et al.* (1997) and Lean and Rind (1998). However over the central Indian region, at 850 hPa, there is decrease of the temperature, probably due to increase in the monsoon rainfall. At 200 hPa there is an increase in the temperature by 0.5°C around 30°N over the Indian region. There is not much change over the oceanic regions south of India. This eventually increases the south-north temperature gradient by $\sim 12\text{-}15\%$ in the enhanced SC scenario.

Figs. 9 (a&b) show wind anomalies at 850 hPa in the two conditions. As 1986 was a weak monsoon year, there was a weak cross equatorial flow and also weak low level jet at 850 hPa. These features are seen from Fig. 9(a). In the enhanced SC scenario, increase in the south westerlies over the Arabian Sea are noticed (Fig. 9b). At 200 hPa, in the control run, the return northerly flow was weak and westerly anomalies span the equatorial region (Fig. 10 a). In the enhanced SC case, the northerly return flow intensified and extended southwards to 5°S latitude (Fig. 10 b). The divergence pattern at 200 hPa (Figs. 11 a & b)

showed the westward shift and intensification in the enhanced SC scenario. Figs. 12 (a&b) show rainfall anomalies in the two conditions. The anomalies changed from negative in the control run to positive in the enhanced SC scenario over the central India. The seasonal rainfall increased from 81 cm in the control run to 87 cm in the enhanced SC condition.

Thus the study clearly shows that the change in the atmosphere circulations in the enhanced SC scenario is conducive to increase the monsoon rainfall. Here, as a simplified case we have considered the period of LFM as 64 years. In the real situations the period may vary between 60-80 years. Hence it would be difficult to pinpoint the exact year of transition from the negative phase to the positive phase of LFM in the solar irradiance. As suggested by Kripalani and Kulkarni (1997), transition might have occurred around 1990, then one can understand the reduced impact of El Nino in the years 1994 and 1997. It would be difficult to arrive at a general conclusion based on the single case study, nevertheless the study has undoubtedly provided the evidence of the impact of solar irradiance on AISMR at low frequency scale.

4. Conclusions

The LFM in AISMR has been shown to be correlated very well with the LFM in solar irradiance. The sensitivity study using COLA GCM has been carried out to test the hypothesis regarding AISMR-solar variability relationship suggested by Mehta and Lau (1997). The study showed that the hypothesis appears to be true in the case study of a seasonal model integration. Based on the previous statistical and modelling studies and results from this study, a modified mechanism of operation between the two has been suggested. In this mechanism, the role played by SSTs over west equatorial Pacific have also been taken into account. This is shown in the Fig. 13. The LFM in the solar irradiance generates the variability on the scale of LFM in the different ocean basins. This generated LFM in the SST variability is in phase with the solar variability (Reid 1991). In the positive phase of solar irradiance, SSTs over Indian ocean are warmer (Reid 1991) and over the east-central-Pacific are cooler (Mehta and Lau 1997). It is well known that the SSTs over east and west equatorial Pacific are out of phase, the equatorial west Pacific are warmer in the positive phase of LFM of solar irradiance. In the positive phase of solar irradiance, the temperatures over the Indian land region will increase. This generates the increased-land-ocean contrast in the positive phase of the solar anomaly. As the SSTs over Indian Ocean are also high, there is

an increased moisture flux over the monsoon region. Also the high SSTs over equatorial west Pacific provides additional low level convergence in this region. The additional moisture flux and the low level convergence provide additional latent heat flux over the Indian land region, which enhances the land-ocean contrast, leading to favourable conditions for the monsoon.

The change in the solar irradiance on the scale of LFM is about 0.15%. However, small positive anomaly in the solar irradiance, consistently heat the oceans which have large heat storage capacity and long memory. The co-operative action of increased moisture flux over the Indian Ocean, increased low level convergence over west equatorial Pacific and increased land ocean contrast together tries to bring AISMR anomalies to the positive side. Some of the shortcomings of the present study are that in the GCM simulation, the spectral dependence of solar modulation is not considered. The photochemical response of ozone to changes in the solar radiation is also not taken into account. Furthermore, there is a need for long-term integration of coupled GCM to estimate the response of increase in SC comprehensively.

Acknowledgements

The authors are thankful to Dr. J. Shukla for providing the COLA GCM used in the present study. They are further thankful to Dr. J. Lean for the solar irradiance data and to Dr. Torres and Dr. Compo for the interactive wavelet transform plot.

References

- Ananthkrishnan, R. and Parthasarathy, B., 1984, "Indian rainfall in relation to the sunspot cycle 1871-1978", *J. Climat.*, **4**, 149-169.
- Bhalme, H. N. and Mooley, D. A., 1981, "Cyclic fluctuations in the flood area and relationship with the Double (Hale) sunspot cycle", *J. Appl. Met.*, **20**, 1041-1048.
- Bhalme, H. N. and Jadhav, S. K., 1984, "The double (Hale) sunspot cycle and floods and droughts in India", *Weather*, **39**, 112-116.
- Bhalme, H. N., Patwardhan, S. K. and Sikdhar, A. B., 1997, "Do persistent rainfall deficit over the western Sahel and frequent drought occurrence in Indian monsoon in recent decades have come to an end ? ", Abstract Volume, P19, INTROMET'97, Dec. 2-5, New Delhi, 90 pp.
- Chui, C. K., 1992: *An Introduction to Wavelets*. Academic Press, Inc., 264 pp.
- Cubash, U., Voss, R., Hegerl, G. C., Waszkewitz, J., Crowley, T. J., 1997, "Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model", *Clim. Dyn.*, **13**, 757-767.
- Daubechies, I., 1988, "Orthonormal Bases of Compactly Supported Wavelets", *Comm. Pure and Appl. Math.* **XLI**, 909 - 996.
- Daubechies, I., 1992, "Ten Lectures on Wavelets CBMS-NSF Regional conf. Ser. in Applied Mathematics", Capital City Press, 357 pp.
- Feynman, J. and Fougere, P. F., 1984, "Eighty-eight-year periodicity in solar terrestrial phenomena confirmed", *J. Geophys. Res.*, **89**, 3023-3027.
- Gadgil, S. and Sajani, S., 1998, "Monsoon precipitation in the AMIP runs", *Climate Dyn.*, **14**, 659-689.
- Gilliland, R. L., 1981, "Solar radius variations over the past 265 years", *Astr. J.*, **248**, 1154-1155.
- Gilliland, R. L., 1982, "Modelling solar variability", *Astr. J.*, **253**, 399-405.
- Gilliland, R. L. and Schneider, S. H., 1984, "Volcanic, CO₂, and solar forcing of Northern and Southern hemisphere surface air temperatures", *Nature*, **310**, 38-41.
- Gu, D. and Philander, S. G. H., 1995, "Secular changes of annual and interannual variability in the tropics during the past century", *J. Cli.*, **8**, 864- 876.
- Grossmann, A. and Morlet, J., 1984, "Decomposition of Hardy Functions into Square Integrable Wavelets of Constant Shape" *S.I.A.M. J. Math. Anal.*, **15**, 723 - 736.
- Haigh, J. D., 1999, "Modelling the impact of solar variability on climate", *J. Atmos. and Terres. Phys.*, **61**, 63-72.
- Hansen, J. et al., 1997, 'Forcings and chaos in interannual to decadal climate change', *J. Geophys. Res.*, **102**, 25679-25720.
- Herman, J. R. and Goldberg R. A., 1985, 'Sun, Weather, and Climate', Dover publications, Inc. New York, 333 pp.
- Houghton, J. T., Meira Filhon, L. G., Bruce, J., Lee, H., Callander, B. A., Haites, E., Harris, N. and Maskell, K. Eds., 1995, "Climatic Change 1994. radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios", Cambridge University Press. 339 pp.

- Jagannathan, P. and Bhalme, H. N., 1973, "Changes in the pattern of distribution of southwest monsoon rainfall over India associated with sunspots", *Mon. Wea. Rev.*, **101**, 691-700.
- Johnsen, S. J., 1970, "Climate oscillations 1200-2000 A.D.", *Nature*, **227**, 482-483.
- Joseph, P. V., 1976, "Climatic change in monsoon and cyclones 1871-1974" In: *Proceedings of Symposium on Tropical Monsoon, IITM, Pune*, 378-387.
- Kelly, P. M. and Wigley, T. M. L., 1992, "Solar cycle length, greenhouse forcing and global climate", *Nature*, **360**, 2486-2522.
- Kinter, J. L. III, Shukla, J., Marx, L. and Schneider, E. K., 1988, "A simulation of the winter and summer circulations with the NMC global spectral model" *J. Atmos. Sci.*, **45**, 2486-2522.
- Kripalani, R. H. and Kulkarni, A., 1997, "Climatic impact of El Nino/La Nino on the Indian monsoon: A new perspective", *Weather*, **52**, 39-46.
- Krishnakumar, K., Soman, M. K. and Rupakumar, K., 1995, "Seasonal forecasting of Indian summer monsoon rainfall", A review, *Weather*, **50**, 449-467.
- Kulkarni, J. R., Sadani, L. K. and Murthy, B. S., 1999, "Wavelet analysis of intermittent turbulent transport in the atmospheric surface layer over a monsoon trough region", *Bound. -Layer Meteor.* **90**, 217-239.
- Kulkarni, J. R., 2000, "Wavelet analysis of the association between the southern oscillation and the Indian summer monsoon", *Int. J. Climat.*, **20**, 89-104.
- Lamb, H. H., 1972, "Climate: Present, Past and Future- Volume 1: Fundamental and climate now", Methuen, London
- Lean, J., Beer, J. and Bradley, R., 1995, "Reconstruction of solar irradiance since 1610: Implications for climate change", *Geophys. Res. Lett.*, **22**, 3195-3198.
- Lean, J. and Rind, D., 1998, "Climate forcing by changing solar radiation", *J. Cli.*, **11**, 3069-3094.
- Lean, J. and Rind, D., 1999, "Evaluating sun-climate relationships since the Little Ice Age", *J. Atmos. and Solar-Terr. Phys.*, **61**, 25-36.
- Mehta, V. M. and Lau, K. M., 1997, "Influence of solar irradiance on the Indian monsoon-ENSO relationship at decadal-multidecadal time scales", *Geophys. Res. Lett.*, **24**, 159-162.
- Mooley, D. A. and Parthasarathy, B., 1984, "Fluctuations in All-India Summer Monsoon Rainfall during 1871-1978", *Climatic Change*, **6**, 287-301.
- Morlet, J., Arens, G., Fourgeau, E., and Giard, D., 1982(a), "Wave propagation and sampling theory- part 1: complex signal and scattering in multilayered media", *Geophysics*, **47**(2), 203 - 221.
- Morlet, J., Arens, G., Fourgeau, E., and Giard, D., 1982(b), "Wave propagation and sampling theory-part 2: sampling theory and complex waves", *Geophysics*, **47**(2), 222 - 236.
- Nesme-Ribes, E., Ferriera, E. N., Sadourny, R., LeTreut, H. and Li, Z. X., 1993, "Solar dynamics and its impact on solar irradiance and terrestrial climate", *J. Geophys. Res.*, **98**, 18923-18935.
- NRC, 1994, "Solar Influences on global change", National Academy Press, 163 pp.
- Pant, G. B., Rupa Kumar, K., Parthasarathy, B. and Borgaonkar, H. P., 1988, "Long-term variability of the Indian summer monsoon and related parameters", *Advances in Atmos. Sci.*, **5**, 469-481.
- Parthasarathy, B., Rupa Kumar, K., and Kothavale, D. R., 1992, "Indian summer monsoon rainfall indices", *Meteor. Mag.*, **121**, 174 - 185.
- Reid, G. C., 1987, "Influence of solar variability on global sea surface temperature", *Nature*, **329**, 142-143.
- Reid, G. C., 1991, "Solar total irradiance variations and the global sea surface temperature record", *J. Geophys. Res.*, **96**, 2835-2844.
- Rind, D., and Overpeck, J., 1993, "Hypothesized causes of decade-to-century climate variability: Climate model results", *Quat. Sci. Rev.*, **12**, 357-374.
- Royer, J. F., Chauvin, F., Plissier, G., 1994, "Sensitivity of the atmospheric circulation to solar irradiance variations". In: Nesme-Ribes, E. (Ed.). *The solar engine and its influence on terrestrial atmosphere and climate*. NATO ASI Series 125, pp. 507-516.
- Sadourny, R., 1994, "Sensitivity of climate to long-term variations of the solar output", In: Nesme-Ribes, E. (Ed.). *The solar engine and its influence on terrestrial atmosphere and climate*. NATO ASI Series 125, 479-492.
- Sela, J. G., 1980, "Spectral modeling at the National Meteorological Center", *Mon. Wea. Rev.*, **108**, 1279-1292
- Sikka, D. R., 1980, "Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulations parameters", *Proc. Indian Acad. Sci. (Earth & Planetary Sci.)*, **89**, 179-195.
- Torrence, C. and Compo, G. P., 1998, "A practical guide to wavelet analysis", *Bull. Ame. Met. Soc.*, **79**, 61-78.

- Torrence, C. and Compo, G. P., 1999, "Interactive Wavelet Plot", <http://paos.colorado.edu/research/wavelets/>
- Verma, R. K., Subramaniam, K. and Dugam, S. S., 1985, "Interannual and long-term variability of the summer monsoon and its possible link with northern hemispheric surface air temperature", *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **94**, 187-198.
- Walker, G., 1915, "Correlations in seasonal variation of weather: IV Sunspots and rainfall", *Indian Met. Mem.*, **21**, 12-16. Also available in "Sir Gilbert Walker Selected papers. Long Range Forecasting of Monsoon Rainfall", IMS publication, 1986, 80-84.
- Wetherald, R. T. and Manabe, S., 1975, "The effects of changing the solar constant on the climate of a general circulation model", *J. Atmos. Sci.*, **32**, 2044-2059.
-