UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR/930 - 17

"Workshop on El Niño, Southern Oscillation and Monsoon"
15 - 26 July 1996

"Influence of Solar Irradiance on the Indian Monsoon-ENSO Relationship at the Multidecadal Time Scales"

K.M. LAU
NASA/Goddard Space Center
Greenbelt, MD
USA

Please note: These are preliminary notes intended for internal distribution only.

MAIN BUILDING STRADA COSTIERA, 11 TEL. 2240111 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449
MICROPROCESSOR LAB. VIA BEIRUT, 31 TEL. 2249911 TELEFAX 224600 TELEX 460392 GALILEO GUEST HOUSE VIA BEIRUT, 7 TEL. 2240311 TELEFAX 2240310 TELEX 460392

Influence of solar irradiance on the Indian monsoon-ENSO relationship at multidecadal time scales

Vikram M. Mehta
NASA-Univ. of Maryland Joint Center for Earth System Science
Department of Meteorology
University of Maryland
College Park, Maryland, U.S.A. 20742
Phone: (301)-286-2390, FAX: (301)-286-1759, e-mail: mehta@atmos.umd.edu

and

W.K.-M. Lau
Code 913, NASA/Goddard Space Flight Center
Greenbelt, Maryland, U.S.A. 20771

To be submitted for publication in *Science*
July 10, 1996

Abstract

The Indian monsoon and the El Niño-Southern Oscillation (ENSO) phenomena affect the lives of several billion people via their effects on agriculture, water resources, fisheries, and public health. It is important to study these phenomena and their variability at various time scales, not only to satisfy intellectual curiosity but also to assess their predictability. Since these two are the strongest phenomena in the tropical climate system, long term predictability of both phenomena might require better understanding of if and how they interact at various time scales. The present study focuses on multidecadal variability of the Indian monsoon and the ENSO.

Area-averaged rainfall over India and sea surface temperature (SST) averaged over the equatorial central and eastern Pacific Ocean as an indicator of the ENSO from 1872 to 1990 are analyzed to study their covariability. The correlation coefficient between the two quantities ranges from -0.8 to -0.2 in various epochs. The correlation coefficient over the 119 years analysis period is -0.57 and is significant at the 99% level. The rainfall and SST undergo decadal-multidecadal variability without any dominant time scale at very low frequencies. The covariability of the two quantities also varies at decadal-multidecadal time scales. Solar irradiance at the top of the Earth's atmosphere during the 119 years analysis period is compared with the monsoon rainfall, the SST, and their covariability. The rainfall and irradiance appear to covary with nearly the same phase at multidecadal time scales. The SST and irradiance appear to covary with nearly opposite phase at multidecadal time scales. The monsoon-ENSO covariability at interannual time scales is also affected by the solar irradiance variability such that the correlation coefficient between the rainfall and SST was -0.7 during periods of above-normal irradiance and was -0.4 during periods of below-normal irradiance. Based on these results, a hypothesis about the influence of solar irradiance in the ENSO-monsoon relationship is formulated and described.

Introduction

The Indian monsoon *(1)* and the El Niño-Southern Oscillation (ENSO) *(2,3)* phenomena affect the lives of several billion people via their effects on agriculture, water resources, fisheries, and public health. It is important to study these phenomena and their variability at various time scales, not only to satisfy intellectual curiosity but also to assess their predictability. Although the Indian monsoon rainfall can be predicted with some accuracy a few days in advance and the anomalous sea surface temperatures (SSTs) in the equatorial central and eastern Pacific due to the ENSO can be accurately predicted a few seasons in advance, the year-to-year and longer term variability in both phenomena can not yet be predicted accurately. Since these two are the strongest phenomena in the tropical climate system, further improvements in the long term predictability of both phenomena might require better understanding of if and how they interact at various time scales.

There have been numerous studies *(1,4,5,6,7,8)* of the possible covariability of the Indian monsoon and the ENSO. The area-averaged monsoon rainfall over India was used in these studies. A qualitative classification of the El Niño (weak, moderate, strong, very strong) was used over much of the analysis period because reliable SST measurements in the equatorial central and eastern Pacific during the first few decades of the 20^{th} Century were not available until recently. Some of these studies also used the Southern Oscillation Index (SOI) (the normalized and detrended surface pressure difference between Papeete and Darwin) to study the ENSO-Indian monsoon relationship. These studies showed that, between 1900 and 1981, 14 out of 34 of the Indian monsoon seasons with below-average rainfall were also the years of ENSO events (above-normal SSTs in the equatorial central and eastern Pacific). During the same period, ENSO events occurred in only two of the 47 Indian monsoons with above-normal rainfall. These results suggest that during the 82 years analysis period, there was 4% probability of ENSO events occurring in above-normal monsoon rainfall years but approximately 40% probability of below-normal monsoon rainfall and ENSO events occurring in the same year.

The earlier mentioned non-availability of SST measurements during the first few decades of the 20^{th} Century in the equatorial central and eastern Pacific until recently restricted the covariability studies to finding qualitative associations between the ENSO and the Indian monsoon. The apparent covariability and its decadal-multidecadal variability could not be quantified for a period longer than the recent 40-50 years. Scientific interest in decadal-multidecadal tropical climate variability is on the increase since such variability was found in the tropical Atlantic *(9,10)*, the tropical Pacific *(11,12)*, and the Indian *(12,13)* Ocean regions in the recently-available Global Ocean Surface Temperature Atlas (GOSTA) *(14)* and other climate data sets.

Variability of solar output has been suggested *(15,16,17,18)* as a possible cause of decadal-multidecadal climate variability. Since solar irradiance is the dominant form of energy driving the terrestrial climate system, it is reasonable to expect that variability in the irradiance might cause terrestrial climate variability. But the evidence of association between decadal-multidecadal solar output variability and terrestrial climate variability has been inconclusive *(15)*.

Much *(15,16,17)* of the earlier work about finding relationships between solar variability and terrestrial climate variability was conducted with some proxy quantities associated with solar variability such as sunspot numbers and 10.7 cm solar flux, but how these proxy quantities physically relate to the Sun's energy output was left to conjectures. Recently, Lean *(9)* has calculated solar irradiance at the top of the Earth's atmosphere (the so-called solar 'constant') making use of sunspot numbers and information about solar faculae since 1600 A.D., observations of other stars, and theories of solar evolution. It has been shown *(20)* that the variations in the estimated solar irradiance and Northern Hemisphere summer temperature over land from 1600 A.D. to the present agree remarkably well. The purpose of the present study was to use a 120 years long SST time series in the equatorial central and eastern Pacific from the GOSTA data set to quantify the covariability between the Indian monsoon rainfall and the ENSO, to see if this covariability undergoes decadal-multidecadal variability, and to compare the rainfall and SST time series with solar irradiance at the top of the atmosphere during the 120 years period to see if the the long term variability of the two quantities is physically consistent with the variability of solar irradiance.

The SST, Indian monsoon rainfall, and solar irradiance data

The SST measurements used in the present work have been extracted from the GOSTA. The SST measurements have been averaged in the region between 150°W-90°W longitudes and 5°S-5°N latitudes to form the so-called Niño3 SST index. A time series of monthly- and annual-average Niño3 SST index from 1872 to 1991 were formed. Since ship routes in the equatorial central and eastern Pacific were few and infrequently traveled before the 1940s, the reliability of the Niño3 index before the 1940s would be doubtful unless it is validated by comparison with some other data. We compared the Niño3 index with qualitative classification of the ENSO severity before the 1920s *(21)* and other estimates of the Niño3 index since the 1920s *(22)*. We found that the Niño3 index formed from the GOSTA data matches the other estimates well.

The so-called 'All-India' monsoon rainfall time series was used in the present work. This is an area-weighted rainfall average over India and spans the period 1871 to 1990. There is 119 years (1872-1990) overlap between the Niño3 SST and the Indian monsoon rainfall time series.

Annual-average solar irradiance *(19)* from 1871 to 1990 was compared with the Niño3 SST and the Indian monsoon rainfall. Since solar irradiance during the first 80-90 years of the analysis period was calculated using sunspot numbers and information about solar faculae, the year of a solar irradiance anomaly is accurate to within ± 1-2 years during the first 80-90 years.

The Niño3 SST and Indian monsoon rainfall variability

A visual inspection of the Niño3 SST and the Indian monsoon rainfall anomaly, shown in Figure 1, indicates that the frequencies and amplitudes of the SST and rainfall anomalies have varied considerably over the 119 years analysis period. The variability of the Niño3 SST and the Indian monsoon rainfall was low during 1880-early 1890s, 1920s-1930s, and 1940-1955. The rainfall variability was high in the early 1970s-1990 period. The average SST anomaly was positive and the average rainfall anomaly was negative during late 1890s to mid 1900s. During the 20 years period from 1941 to 1960, there were five weak, positive SST anomalies and three negative rainfall anomalies, so the average SST was below-normal and the average rainfall was above-normal during this period. The visual inspection also shows that whereas almost all positive SST anomalies were associated with negative rainfall anomalies within ± 1 year, negative rainfall anomalies also occurred even in the absence of substantial, positive SST anomalies.

The preponderance of simultaneous, opposite-polarity SST and rainfall anomalies is also confirmed quantitatively. The correlation coefficient between the Niño3 SST and the Indian monsoon rainfall anomaly time series is -0.57 which, for the 119 years long time series, is significant at the 99% level taking into account the autocorrelation within each time series. 'Moving-window' correlation coefficients in some decadal-multidecadal intervals is as high as -0.8 or as low as -0.2. Histograms (Fig. 2) of rainfall anomalies for positive and negative SST anomalies also show that there are many more negative rainfall anomalies when the SST anomalies are positive than when they are negative.

The estimated Fourier cross-spectrum (not shown) between the Niño3 SST and rainfall anomaly time series has high coherence and opposite polarities between the two quantities at most Fourier frequencies, confirming the above results. The estimated Fourier spectra (not shown) of the two quantities, however, do not have significant peaks at decadal-multidecadal time scales. So, the high coherence between the SST and rainfall at decadal-multidecadal time scales appears to be between slow, 'meandering' variability in both quantities without there being dominant decadal-multidecadal time scales in either of them. In order to separate the multidecadal component, we filtered the rainfall and SST time series with a low-pass filter that allows the amplitudes at periods equal to or longer than 24 years to pass through without any attenuation and completely attenuates the amplitudes at periods shorter than 24 years. The two filtered time series are shown in Figure 3. Both time series show multidecadal, opposite-polarity anomalies in SST and rainfall, especially between approximately 1900 and 1975. This may be natural variability of the climate system, but since solar irradiance during the 20th Century is known *(20)* to vary and since this variation has been correlated *(20)* with the Northern Hemisphere summer temperatures over land, we compared the multidecadal variability in the Indian monsoon rainfall and Niño3 SST with solar irradiance variations.

The role of solar irradiance variability in the Indian monsoon and ENSO variability

A visual inspection of the solar irradiance time series shows variability at decadal-multidecadal time scales. We filtered the solar irradiance time series with the same low-pass filter used for the Niño3 SST and the Indian monsoon rainfall. The filtered solar irradiance time series is also shown in Figure 3. The solar irradiance and monsoon rainfall anomalies appear to covary with the same polarity since approximately the mid 1890s. Both were below-normal during the late 1890s-the mid 1930s and the mid 1960s-early 1980s. Both were above-normal during the mid 1930s-mid 1960s. The Niño3 SST and solar irradiance anomalies appear to have opposite polarities over much of the 120 years analysis period. The comparison between solar irradiance and Niño3 SST anomalies (Fig. 3) shows that the SST was above-normal when solar irradiance was below-normal (1890-1936) and the SST was below-normal when solar irradiance was above-normal (1875-1889, 1937-1960). If the multidecadal variability in these two quantities are physically related, it is difficult to understand how an increase in solar heat flux cools the Niño3 SST unless the possible effect of the irradiance increase on the tropical Pacific winds and dynamical air-sea interaction are included in the relationship. Assuming that the multidecadal variability in solar irradiance causes the multidecadal variability in the Indian monsoon rainfall and the Niño3 SST, we have formulated the following hypothesis to explain the physical connection among the three quantities.

The seasonal reversal of the monsoon winds over India is controlled *(1)* by the seasonal reversal of the land-ocean heating gradient. Since the Indian subcontinental landmass has much smaller heat capacity than the Indian Ocean, the Arabian Sea, and the Bay of Bengal, the temperature of the landmass would increase/decrease almost simultaneously with increasing/decreasing solar irradiance. Although the amplitude of the multidecadal solar irradiance variability is small (approximately 1 W·m^{-2} valley-to-peak), a small-amplitude anomaly of positive polarity would bias the solar irradiance incident on the Indian subcontinent 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. Even if evaporation does not increase in response to above-normal solar irradiance, an above-normal moisture flux (due to stronger winds) might result in above-normal rainfall over India. It is also possible that a positive feedback mechanism in the monsoon atmosphere-land-ocean system might increase the response to the solar irradiance anomaly. Thus, it is plausible that the multidecadal solar irradiance variability can cause the multidecadal Indian monsoon rainfall variability.

The Niño3 SST can decrease if the near-surface, easterly winds over the tropical Pacific strengthen and increase the upwelling of colder water from below the ocean thermocline. Relatively small changes in the easterly winds in the central and eastern Pacific can cause substantial changes in the upwelling because the thermocline, separating the warmer surface water from the colder subsurface water, is usually near the surface in this region. It is the vertical movement of the thermocline in response to wind changes that is supposed to create the warm and cold SST anomalies of the ENSO 'cycle'. If the Indian monsoon wind system, the east-west circulation in the tropical atmosphere, and the Walker circulation interact, a strengthening of the monsoon winds might also strengthen the near-surface easterly winds over the tropical Pacific which, in turn, might cool the Niño3 SST by the mechanism described above. The nearly in-phase rainfall and solar irradiance anomalies, and the nearly-opposite polarity Niño3 SST and Indian monsoon rainfall anomalies in Figure 3 support this hypothesis.

The interannual variability in the ENSO and the Indian monsoon occurs in the presence of and is apparently affected by this solar variability-forced multidecadal variability. The histograms of all rainfall and SST anomalies for above-normal and below-normal solar irradiance are shown in Figure 4. When the irradiance is above-normal, there are many more large (1.5-2 standard deviations) rainfall anomalies than when the irradiance is below-normal. There are many more large (0.5-2, above-normal Niño3 SST anomalies when solar irradiance is below-normal. The correlation coefficient between the unfiltered rainfall and SST anomalies during the 26 years period (1940-65) when the irradiance was above-normal is -0.7 and the coefficient during the 20 years period (1966-85) when the irradiance was below-normal is -0.4. The correlation coefficient (-0.7) during the former period is significant at the 99% level, but the coefficient (-0.4) during the latter period is not significantly different from zero at the 99% level. During other periods of high or low solar irradiance also the correlation coefficient is high or low, respectively. This suggests that there is a stronger coupling between the interannual variability of the Indian monsoon and the ENSO when solar irradiance is above-normal and the stronger monsoon winds 'drive' the tropical Pacific wind system to cool the equatorial central and eastern Pacific SSTs for several decades. The coupling between the two wind systems may be weaker when solar irradiance is below-normal, reducing the upwelling and warming the Niño3 SSTs.

The results of this study are suggestive rather than definitive because the monsoon rainfall, the Niño3 SST, and the solar irradiance time series contain only a few samples of the multidecadal variability. Neverthless, it is quite obvious that the monsoon rainfall and the Niño3 SST anomalies have opposite polarities during much of the analysis period, and that both these quantities and the correlation between them undergo decadal-multidecadal variability. It seems plausible that solar irradiance exercizes a major influence on the Indian monsoon at multidecadal time scales. It also seems plausible that the interaction between the monsoon wind system and the tropical pacific wind system may be a major factor in multidecadal variability of the equatorial central and eastern Pacific SSTs. The role of solar irradiance in the Indian monsoon and the ENSO at multidecadal time scales is being studied further with analyses of observations and ocean-atmosphere general circulation models.

Acknowledgements The authors are grateful to Judith Lean for the use of the solar irradiance time series, and to Jagadish Shukla and Dan Paolino for the use of the Indian monsoon rainfall data. This work was partially supported by NOAA grant NA93AANAGO349.

References

1. *Monsoons*, J. Fein and P. Stephens, Eds. (Wiley-Interscience, John Wiley & Sons, 1987).
2. S.G. Philander, *El Niño, La Niña, and the Southern Oscillation*, vol.46, International Geophysics Series, (Academic Press, 1990).
3. *Teleconnections connecting world-wide climate anomalies*, M. Glantz, R. Katz, and N. Nicholls, Eds., (Cambridge University Press, 1991).
4. J.K. Angell, *Mon. Wea. Rev.*, **109**, 230(1981).
5. E.M. Rasmusson and T.H. Carpenter, *Mon. Wea. Rev.*, **111**, 354(1983).
6. C.F. Ropelewski and M.S. Halpert, *Mon. Wea. Rev.*, **115**, 1606(1987).
7. — and —, *J. Climate*, **2**, 268(1989).
8. P.J. Webster and S. Yang, *Quart. J. Roy. Met. Soc.*, **118**, 877(1992).
9. V.M. Mehta and T. Delworth, *J. Climate*, **8**, 172(1995).
10. — and V.K. Dubey, Submitted to *J. Climate.*
11. J.F. Shriver and J.J. O'Brien, *J. Climate*, **8**, 2762(1995).
12. V.M. Mehta, In preparation for *J. Climate.*
13. Allan et al., *J. Climate*, **8**, pp(1995).
14. M. Bottomley, C.K. Folland, J. Hsiung, R.E. Newell, and D.E. Parker, "Global Ocean Surface Temperature Atlas (GOSTA)", Her Majesty's Stationary Office, London (1990).

15. A.B. Pittock, *Quart. J. Roy. Met. Soc.*, **109**, 23(1983).

16. K. Labitzke and H. van Loon, *Ann. Geophysicae*, **11**, 1084(1993).

17. T.P. Barnett, *Geophys. Res. Lett.*, **16**, 803(1989).

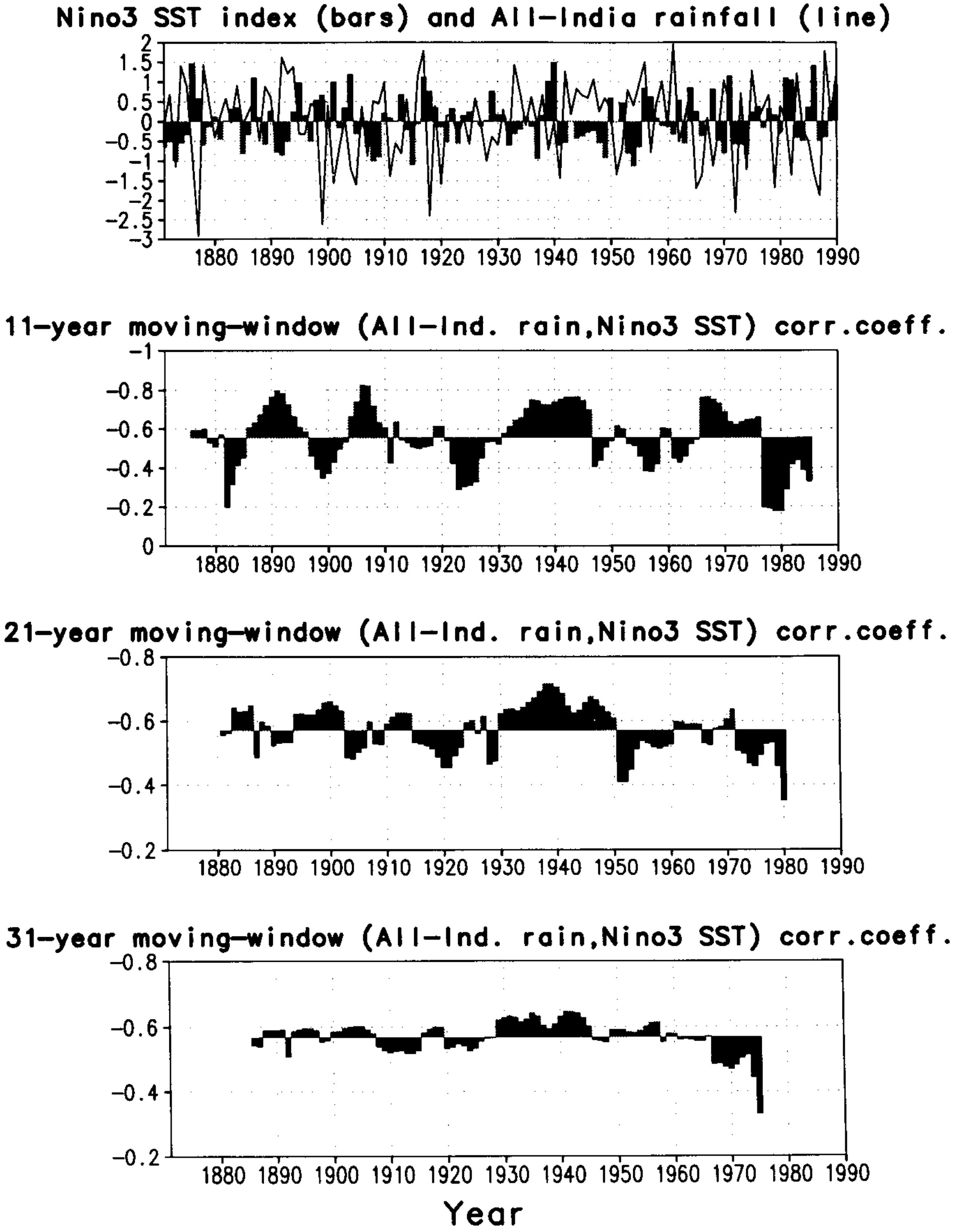
18. G.C. Reid, *J. Geophys. Res.*, **96**, 2835(1991).

19. J. Lean, *Rev. Geophys.*, **29**, 505(1991).

20. J. Lean, J. Beer, and R.S. Bradley, *Geophys. Res. Lett.*, in press.

21. W.H. Quinn, D.O. Zopf, K.S. Short, and R.T.W. Kuo Yang, *Fish. Bull.*, **76**, 663(1978).

22. E.M. Rasmusson and T.H. Carpenter, *Mon. Wea. Rev.*, **110**, 354(1982).



Nino3 SST index (bars) and All-India rainfall (line)

11-year moving-window (All-Ind. rain,Nino3 SST) corr.coeff.

21-year moving-window (All-Ind. rain,Nino3 SST) corr.coeff.

31-year moving-window (All-Ind. rain,Nino3 SST) corr.coeff.

Figure 1

Difference between frequency distributions for above-normal and below-normal Nino3 SST

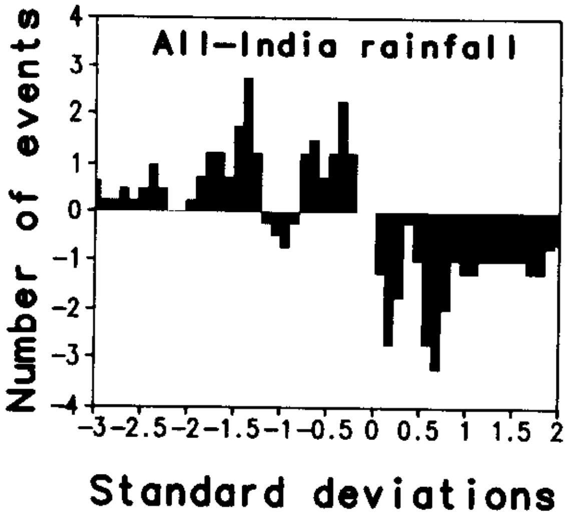
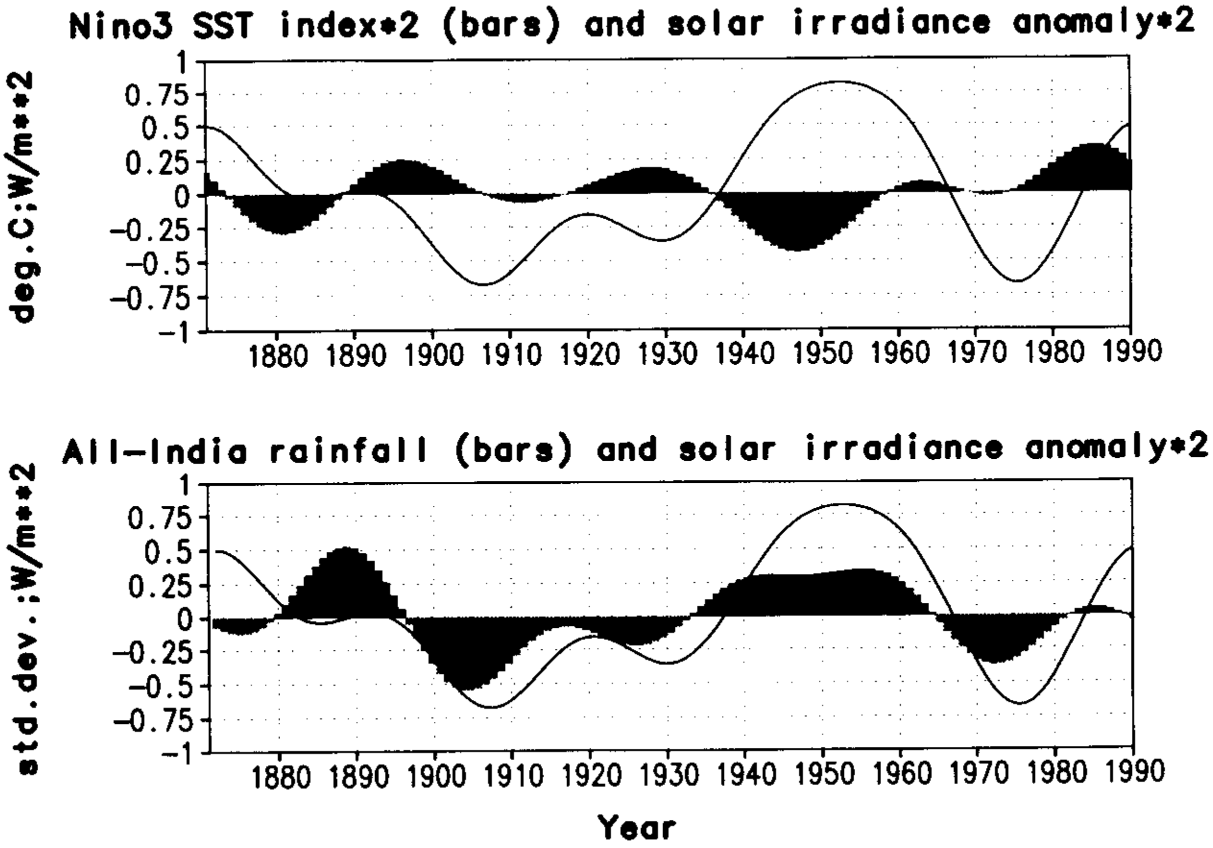


Figure 2


Nino3 SST index*2 (bars) and solar irradiance anomaly*2
deg.C;W/m**2
1
0.75
0.5
0.25
0
−0.25
−0.5
−0.75
−1
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
All-India rainfall (bars) and solar irradiance anomaly*2
std.dev.;W/m**2
1
0.75
0.5
0.25
0
−0.25
−0.5
−0.75
−1
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

Figure

Difference between frequency distributions
for above-normal and below-normal solar irradiance

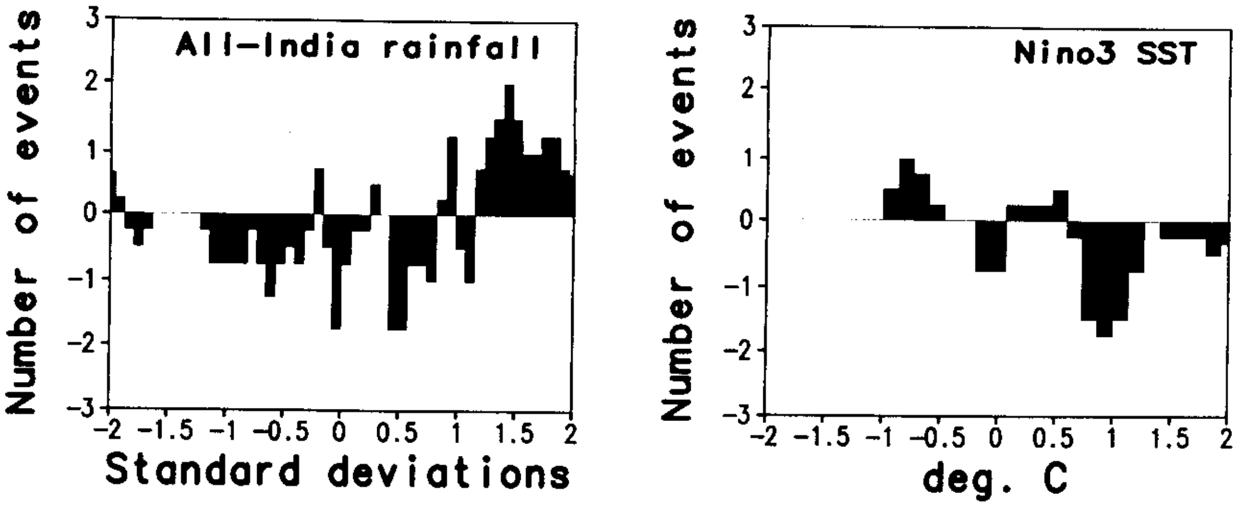


Figure 4