Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data

M. Rajeevan,[1] Jyoti Bhate,[1] and A. K. Jaswal[1]

Received 28 June 2008; revised 13 August 2008; accepted 18 August 2008; published 20 September 2008.

[1] In this study, using 104 years (1901–2004) of high resolution daily gridded rainfall data, variability and long-term trends of extreme rainfall events over central India have been examined. Frequency of extreme rainfall events shows significant inter-annual and inter-decadal variations in addition to a statistically significant long term trend of 6% per decade. Detailed analysis shows that inter-annual, inter-decadal and long-term trends of extreme rainfall events are modulated by the SST variations over the tropical Indian Ocean. The present study supports the hypothesis that the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean. In the global warming scenario, the coherent relationship between Indian Ocean SST and extreme rainfall events suggests an increase in the risk of major floods over central India. **Citation:** Rajeevan, M., J. Bhate, and A. K. Jaswal (2008), Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data, *Geophys. Res. Lett.*, *35*, L18707, doi:10.1029/2008GL035143.

1. Introduction

[2] One of the most significant consequences of global warming due to increase in greenhouse gases would be an increase in magnitude and frequency of extreme precipitation events. Climate model simulations [*Hennessey et al.*, 1997] and empirical evidences confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events and therefore increase risks of floods [*Intergovernmental Panel on Climate Change (IPCC)*, 2007]. Any positive or increasing trend in extreme rainfall events is a serious concern. The recent extreme heavy rainfall event (94.4 cm in 24 hours) occurred over Mumbai on 26 July 2005 prompts us to think whether there is any significant trend in extreme rainfall events over India. The recent empirical studies have shown that worldwide there is an increasing trend of extreme precipitation events [*Groisman et al.*, 2001; *Haylock and Nicholls*, 2000; *Alexander et al.*, 2006; *Klein Tank et al.*, 2006; *Guhathakurta and Rajeevan*, 2007; *Sen Roy and Balling*, 2004].

[3] A recent study by *Goswami et al.* [2006] using a high resolution daily gridded rainfall data set [*Rajeevan et al.*, 2006] showed that there are significant rising trends in the frequency and the magnitude of extreme rain events over central India during the monsoon season. The study also showed that significant decreasing trend in the frequency of moderate events during the same period, thus leading to no significant trend in the mean rainfall. However, the evolution of monsoon rainfall statistics through the 20th century is dominated by variations on the interannual to inter-decadal time scale. It is worthwhile to reexamine this problem using a longer time series of rainfall data and to further examine its link with the SST variations over the tropical Indian Ocean. In this study, variability and long term trends of extreme rainfall events over India have been examined in detail using 104 years (1901-2004) gridded daily rainfall data. Possible links with the SST variations over the tropical Indian Ocean also have been explored.

2. Development of Daily Gridded Rainfall Data Set

[4] In 2006, IMD has brought out a high resolution daily gridded rainfall data set for the period 1951–2004 [*Rajeevan et al.*, 2006] using 2140 stations, which was extensively used for many monsoon related studies [*Goswami et al.*, 2006; *Krishnamurthy and Shukla*, 2008; *Ajayamohan and Rao*, 2008]. Since IMD has its archival daily rainfall data of more than 100 years for many stations, a daily gridded rainfall data set for a longer period (1901–2004) was developed. For this analysis, we have considered 1384 stations which had a minimum 70% data availability during the analysis period in order to minimize the risk of generating temporal inhomogeneities in the gridded data due to varying station densities. Multi-stage quality control of observed rainfall data was carried out before interpolating station rainfall data into regular grids of 1° Lat $\times$ 1° Long. The network of stations (1384 stations) considered for this study is shown in Figure 1a.

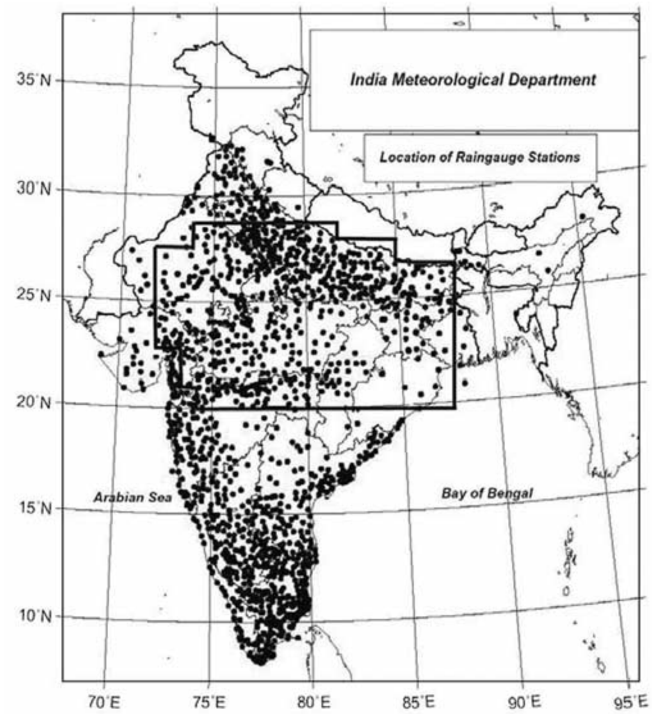
[5] We have used the interpolation method proposed by *Shepard* [1968] for interpolating station rainfall data into regular grids including the directional effects and barriers. The quality of the present data set was examined by comparing with the similar kind of data set developed for the period 1951–2004 [*Rajeevan et al.*, 2006] and found that the present analysis is comparable (Figure S1 of the auxiliary material).[1] Since the present analysis uses a fixed rainfall network, the present data set can be used for examining long term rainfall trends.

[6] For analyzing the variations of sea surface temperatures over the equatorial Indian Ocean and to associate with

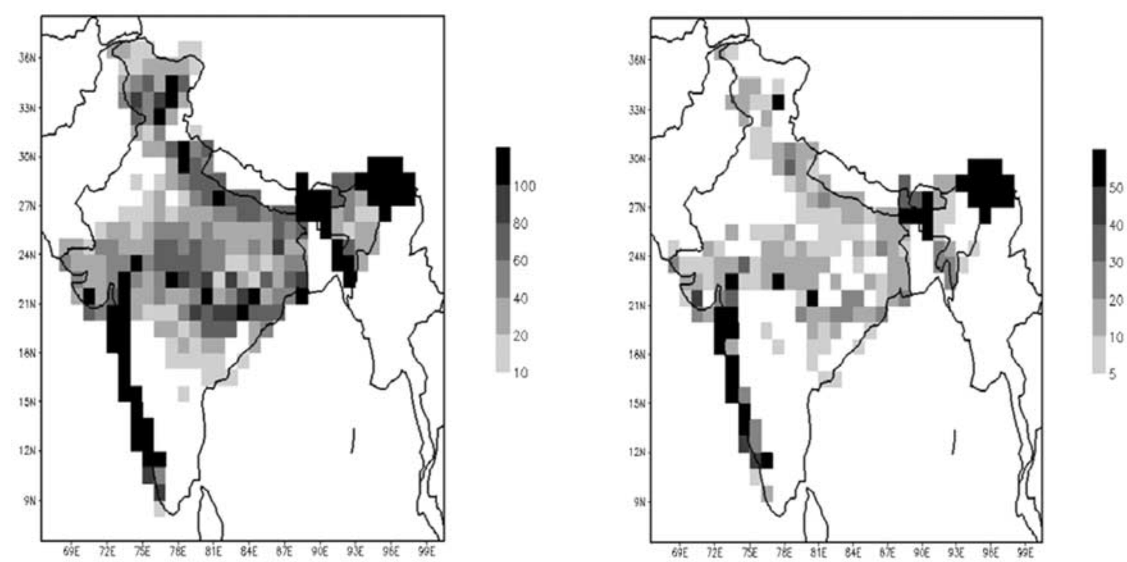
[1]National Atmospheric Research Laboratory, Tirupati, India.

0094-8276/08/2008GL035143$05.00

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035143.



(a)



(b)

Figure 1. (a) The network of rain-gauge stations used for developing the high resolution daily gridded rainfall data set (1901–2004). The box marked is used to analyze the extreme rainfall events. (b) Total number of (left) heavy rain events and (right) very heavy rain events during the monsoon seasons of 1901–2004.

the variations of extreme rainfall events, NOAA Extended Reconstructed SST (ERSST) Version 2 data set [*Smith and Reynolds*, 2004] was also used. This data set contains monthly SST values at 2° Lat X 2° Long resolutions.

3. Analysis of Extreme Rainfall Events Over India

[7] As done by *Goswami et al.* [2006], we have considered the rainfall events between 5 and 100 mm/day as moderate events and rainfall events between 100 and 150 mm/day as

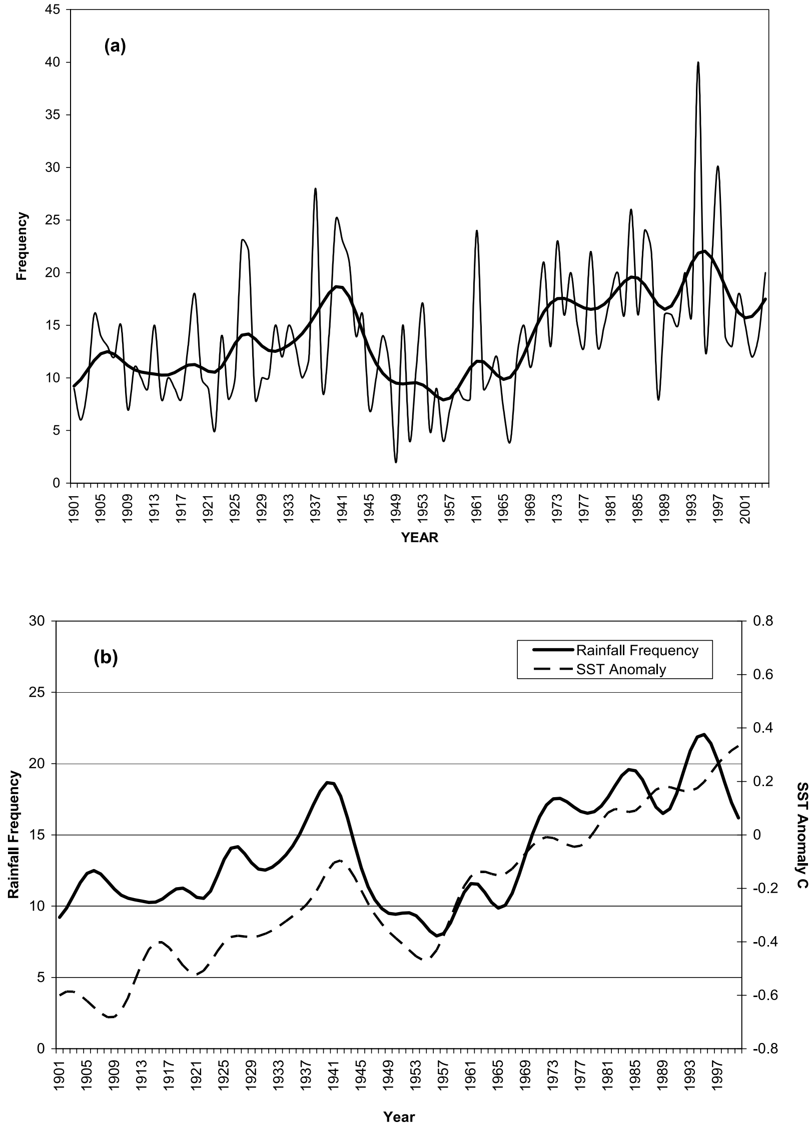


Figure 2. (a) Temporal variation of frequency of very heavy rainfall events (R $\geq$ 150 mm/day) over central India (thin solid line) and its smoothed variation (thick solid line) for the period 1901–2004. (b) Smoothed variation of frequency of very heavy rainfall events over central India and SST anomalies over the Equatorial Indian Ocean. The smoothing has been done to remove the sub-decadal fluctuations using a 13-point filter [*IPCC*, 2007].

heavy rain (HR) events. Rainfall events equal or greater than 150 mm/day are termed as very heavy rain (VHR) events.

[8] Figure 1b shows the spatial variation of extreme rain events during the monsoon season (June to September) for the period 1901–2004. Extreme rainfall events are observed along the west coast of India, NE India and Central India. To examine the variability and long term trends of extreme events, we have considered a large area covering the central India as shown in Figure 1a (box), where occurrence of extreme events is more frequent. This box is slightly different from the box considered by *Goswami et al.* [2006]. The time series of average frequency of VHR events (rain events equal or more than 15 cm) over the central India for the period 1901–2004 is shown in Figure 2a. The time series is smoothed with a 13-point filter [*IPCC*, 2007] to remove fluctuations on less than decadal time scale and is shown as a thick solid line. The mean frequency of VHR events during the monsoon season is 14 and its standard deviation is 6. The time series shows large year to year variations as well as significant inter-decadal variations. VHR events were more frequent in 1920s and 1930s and again during 1980s and 1990s. During the 1940s and 1950s, frequency of VHR events was below average. Over the period, 1901–2004, the frequency time series, however, shows an increasing trend of about 0.8 events per decade, or 6% per decade. This trend is smaller than the trend obtained by *Goswami et al.* [2006] for the period 1951–2000, which is about 10% per decade, due to large inter-decadal variations observed in the time series, as discussed above. The trend for the recent period 1951–2004 is 2.2 events per decade or about 14.5%. All these trend values are significant at 99% significance level. It is interesting to note the significant increase in the frequency of VHR events after mid 1970s. Consistent with the results of *Goswami et al.* [2006], the present analysis also suggests that the frequency of moderate rain events (rainfall between 5 and 100 mm) has

Table 1. Percent Variance Explained by Different Eigenmodes of SST and the Correlation Coefficients With Detrended Extreme Rainfall Frequency, IOD Index, and ENSO Index

		Correlation Coefficients[a]				
		Detrended Extreme Rainfall Frequency			IOD Index	ENSO Index
	Percent Variance (%)	1901–2004	1951–2004	1977–2004	1951–2004	1951–2004
EOF Mode-1	48.8	0.14	0.02	−0.34	0.36**	0.59**
EOF Mode-2	14.5	−0.20*	−0.36**	−0.52**	−0.89**	0.23
EOF Mode-3	10.5	−0.048	0.03	0.09	−0.06	−0.21
EOF Mode-4	6.2	0.18	0.32*	0.03	−0.13	−0.02

[a]Here * means significant at 95% level and ** means significant at 99% level.

decreased over the period 1901–2004 (Figure S2). These observations are consistent with the climate model simulations in response to an equilibrium doubling of carbon dioxide [*Hennessey et al.*, 1997].

[9] Possible links of these observed variability and trends in the extreme rain events with sea surface temperatures over the tropical Indian Ocean are further explored. Figure 2b shows the simultaneous variations of the frequency of VHR events over the central India and SST anomalies averaged over the equatorial Indian Ocean. Both the time series are smoothed with a 13-point filter [*IPCC*, 2007] to remove fluctuations on less than decadal time scale. It is interesting to see the coherent variation of frequency of VHR events and SST anomalies over the equatorial Indian Ocean. The decreasing trend of frequency of VHR events from 1940 to 1960 during the cooling phase of SST and the increasing trend of VHR events from 1960s during the warming phase of SST are noted. The cooling phase of SST from 1940 to 1960 was evident over the equatorial Pacific Ocean also [*IPCC*, 2007]. This suggests that the inter-decadal variability

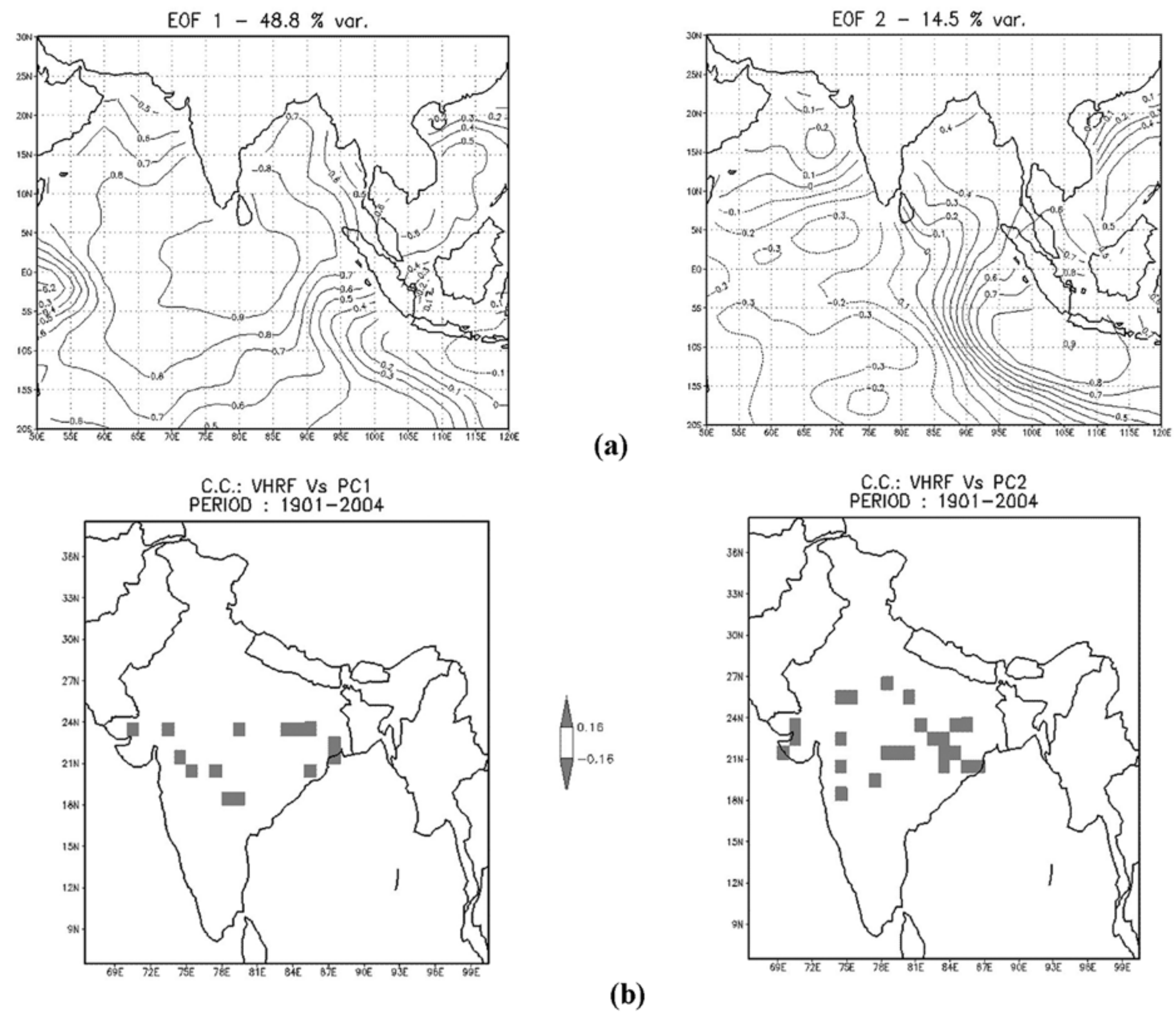


Figure 3. Spatial variation of (a) loading of JJAS averaged detrended SST anomalies over the tropical Indian Ocean for (left) mode-1 and (right) mode-2. Percent of variance explained by the modes are shown above each plot. (b) Correlations of the frequency of VHR events with PC time series of (left) mode-1 and (right) mode-2. Period of analysis: 1901–2004. Correlations significant at 90% level are shaded.

of frequency of VHR events over the central India may be linked to the variations of SST over the equatorial Indian Ocean.

[10] To further establish the relationship between the SST variations over the tropical Indian Ocean and VHR events, an Empirical Orthogonal Function (EOF) analysis of detrended seasonal (June to September) SST anomalies over the tropical Indian Ocean has been carried out. The first five Eigenmodes together contribute 85% of SST variability as shown in Table 1. The loading of the first two EOFs are shown in Figure 3a. The first EOF mode has the maximum loading over the equatorial central Indian Ocean, while the second mode has a dipole structure with opposite loading factors between the west and east Indian Oceans. The first mode has the highest correlation (0.59) with ENSO (Nino 3.4) index and the second mode has the highest correlation (0.89) with the Indian Ocean Dipole Index (SST anomaly difference between the east and west Indian Oceans). Interestingly, as shown in Table 1, this second mode, which has an Indian Ocean Dipole structure, has the highest correlation with the frequency of VHR events over the central India. The correlations for all the three periods are statistically significant. *Ajayamohan and Rao* [2008] have shown that the frequency of heavy rain events over the central India was modulated by frequent IOD events occurred over the Indian Ocean during the recent years. The study by *Kripalani and Kumar* [2004] revealed a dominance of the negative phase of the dipole mode during the earlier decades (1880–1920) and a positive phase during recent decades (1960–2000) with suppressed activity in between. The time series of VHR events (Figure 2a) also showed similar inter-decadal variations. In the time series shown in Figure 2a, there are large peaks of VHR events in 1961, 1994 and 1997, all positive IOD years. The correlation maps (Figure 3b) between the principal component (PC) time series of the first two Eigenmodes of SST with the frequency of VHR events show significant influence of SSTs over the tropical Indian Ocean. In comparison, the time series of the second mode (with IOD structure) has shown stronger correlations. Even though, frequency of VHR events peaked during the recent positive IOD years, Figures 2a and 2b clearly show that increasing trend of VHR events is not merely a reflection of the frequency of IOD events.

4. Discussions

[11] It is shown here that inter annual and inter-decadal variability of extreme rain events over India is influenced by the SST variations over the tropical Indian Ocean. These associations are supported using basic theory and climate model simulations. As the climate warms in response to increases in greenhouse gases, the concentrations of water vapor are expected to increase due to atmospheric increasing water-holding capacity. Some recent studies [*Ross and Elliot*, 2001; *Trenberth et al.*, 2005; *Soden et al.*, 2005] using radio-sonde measurements and satellite data have demonstrated an increase in the total column water vapor and moistening of upper troposphere over the global oceans.

[12] The study of *Trenberth et al.* [2005] revealed that linear trends of column integrated water vapor over the north Indian Ocean around the Indian continent is 4-5% per decade. High quality surface humidity data from early 1900s are not available to examine whether surface water vapor flux also has shown a similar inter-decadal variations like SST and extreme rain events as discussed above. However, an analysis has been made with limited data from the ICOADS archive [*Worley et al.*, 2005]. The data density from the ICOADS data shows a sharp decline in number of observations in 1940s due to the Second World War. Therefore, the analysis has been made only with data from 1951. The analysis of ICOADS data shows statistically significant increasing trend in near-surface water vapor content and surface mean wind speed (Figures 4a and 4b) over the equatorial Indian Ocean during the monsoon season. An increase in the surface water vapor and wind speed suggests an increase the evaporative flux from the Ocean surface and more moisture availability. These observations support the existing hypotheses about the role of atmospheric water vapor content in the frequency of the heavy rainfall events.

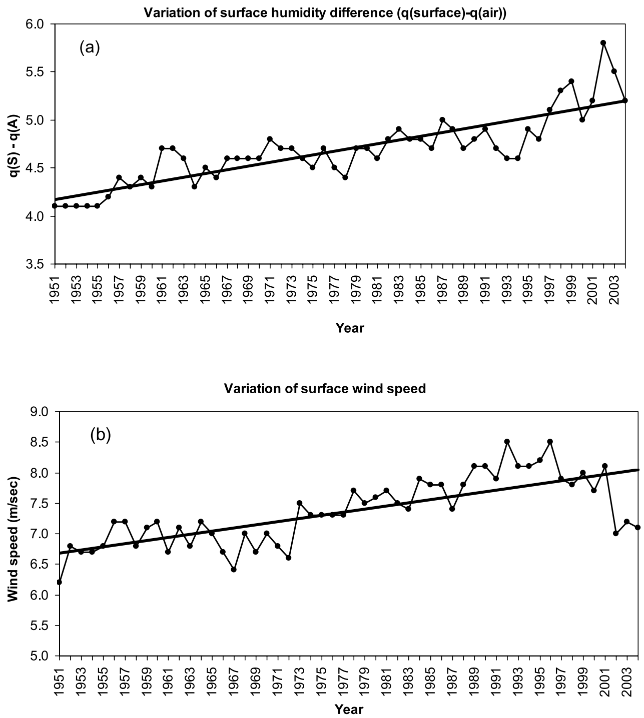


Figure 4. Variation of (a) surface humidity difference and (b) surface wind speed averaged over the equatorial Indian Ocean during the monsoon season. Period: 1951–2004.

[13] The review by *Trenberth et al.* [2003] argued that heavy rainfall rates greatly exceed evaporation rates and thus depend on low-level moisture convergence. In that case, the rainfall intensity should also increase at about the same rate as the moisture increase. The studies [*Trenberth*, 1998, 1999] argued that increasing the moisture content of the atmosphere should increase the rate of precipitation locally by invigorating the storms and depressions through latent heat release and further by supplying more moisture. We demonstrated the simultaneous decreasing trend in SST and VHR events from 1940s to 1960s and an increasing trend in the first four decades of the 20th century. This lends support to the hypothesis that the increasing trend in the last five decades could be associated with the increasing trend of

the Indian Ocean SST. Future climate projections by coupled models suggest a further increase in SST over the equatorial Indian Ocean. The strong coupling between the equatorial Indian Ocean SST and VHR events over the central India suggests that in the present global warming scenario, the frequency of VHR events and risk of floods may increase over the central India.

[14] **Acknowledgments.** We are thankful to J. Srinivasan, IISc Bangalore, for his interest and offering us several valuable suggestions and comments to improve the quality of the paper. We are also thankful to two anonymous reviewers for their critical comments and suggestions.

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J. Bhate, A. K. Jaswal, and M. Rajeevan, National Atmospheric Research Laboratory, Tirupati, 517502, India. (rajeevan61@yahoo.co.in)