Inter-annual relationship between Atlantic sea surface temperature anomalies and Indian summer monsoon

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[1] In this study, the simultaneous inter-annual relationships between SST anomalies over the Northwest Atlantic Ocean and southwest monsoon rainfall over the monsoon core region have been examined using monthly SST and atmospheric data for the period 1951–2005. Statistical analyses reveal significant inter-annual simultaneous relationship between the SST anomalies over North Atlantic and rainfall over the monsoon core region, but with significant epochal variations. The relationship has become stronger after mid-1970s when the El Nino-Indian monsoon relationship has weakened. Positive SST anomalies over the North Atlantic Ocean shift the North Atlantic Jet northwards and the associated circulation changes in the upper troposphere influence Indian monsoon through the circumglobal teleconnection across central Asia. The present study, thus highlights the important role of North Atlantic Ocean as an important source of inter-annual variability of the Indian summer monsoon. **Citation:** Rajeevan, M., and L. Sridhar (2008), Inter-annual relationship between Atlantic sea surface temperature anomalies and Indian summer monsoon, *Geophys. Res. Lett.*, *35*, L21704, doi:10.1029/2008GL036025.

1. Introduction

[2] The interannual variation of the Indian summer monsoon rainfall (ISMR) has a large impact on the agricultural production and hence the economy of the country. A major advance in our understanding of the interannual variation of the monsoon occurred in the eighties with the discovery of a strong link with ENSO. However, it does not explain all of the variance of the ISMR. For example, *Kripalani and Kulkarni* [1996] suggested that about 50% of droughts in India are associated with ENSO. Some part of the inter-annual variation may be influenced by some other climate factors like variations of snow cover over Eurasia [*Kripalani and Kulkarni*, 1999; *Bamzai and Shukla*, 1999] and Indian Ocean SST anomalies [*Rajeevan et al.*, 2002]. The intriguing monsoon seasons of 1997 and 2002 triggered studies which suggested a link to events over the equatorial Indian Ocean [*Gadgil et al.*, 2004].

[3] Recent studies have shown evidences of the influence of North Atlantic SST anomalies on Indian monsoon, especially on mutli-decadal time scale [*Goswami et al.*, 2006; *Li et al.*, 2008]. They showed that the Atlantic Multi-Decadal Oscillation (AMO) produces persistent weakening (strengthening) of the meridional gradient of tropospheric temperature (TT) by setting up negative (positive) TT anomaly over Eurasia. The study by *Li et al.* [2008] using atmospheric model simulations also showed that warm extratropical North Atlantic SSTs induce an arching extratropical wavetrain response, enhancing Indian monsoon rainfall.

[4] In this paper, we discuss the simultaneous inter-annual relationship between SST and circulation anomalies over the North Atlantic and Indian summer monsoon rainfall (ISMR) and its possible physical linkage through the atmospheric circulation anomalies over Eurasia. We demonstrate here that the north Atlantic Ocean influences Indian summer monsoon on inter-annual time scale also.

2. Data

[5] In this study, we have considered the July-August-September period for examining the relationship over the monsoon coherent zone as shown in Figure 1 (top). Over this geographical area (monsoon core zone), the distribution of southwest monsoon rainfall is homogenous. For preparing the rainfall time series, the sub-divisional rainfall data archived at the India Meteorological Department have been used. The mean (July–September) rainfall over the monsoon core region is 691 mm with a coefficient of variation (CV) of 17%. Figure 1 (bottom) shows the year to year variation of seasonal rainfall (July-August-September) over the monsoon core region. The seasonal (JAS) monsoon rainfall over the monsoon core region (ICMR) is considered for further analysis. For the canonical correlation analysis, we have used the gridded rainfall data developed by *Rajeevan et al.* [2006]. This gridded data set was developed using quality controlled 2140 stations spread over the country. For analyzing sea surface temperature variations, the NOAA Extended Reanalysis SST (ERSST) data for the period 1951–2005 have been used. Monthly sea surface temperature (SST) data on a $2^\circ \times 2^\circ$ grid have been derived from the latest version (version 2) updated ERSST.V2 [*Smith and Reynolds*, 2004] SST data. In addition, we have considered the monthly NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] for examining the relationship in surface pressure, surface wind, and upper air winds. We have considered all these data for a common period of 1951–2005.

3. Statistical Relationships

[6] The spatial pattern of statistical correlations between the SST anomalies and ICMR are shown in Figure 2. For examining the changes in the epochal variations, we have calculated the correlation coefficients for two different periods, 1951–1975 and 1976–2005. The spatial patterns

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show statistically significant correlations between the SST anomalies over the NW Atlantic Ocean and ICMR during the simultaneous period (JAS). The correlations suggest that the positive SST anomalies over NW Atlantic region are conducive for above normal monsoon rainfall over the monsoon core region. However, the correlations showed significant epochal variations as shown in Figure 2. The relationships were statistically significant only during the recent period 1976–2005. During the earlier period of 1951–1975, we find that the SST anomalies over the south Atlantic region are well correlated with ICMR [*Kucharski et al.*, 2008]. However, as shown in Figure 2, those correlations have become weaker during the later epoch, while the SST anomalies over the north Atlantic are better correlated with statistical significance.

[7] To further explore the epochal variations of the relationship and to examine the physical relationship, an index was derived by averaging SST anomalies over the NW Atlantic (30°–40°N, 40°–65°W) over the JAS period. The index is termed here as North West Atlantic Index (NWAI). The 21-year running correlations between the NWAI and ICMR are shown in Figure 3. For comparison, the correlations between the Nino 3.4 index and ICMR also are shown with the sign of the correlation coefficient reversed. It shows that the correlations between the NWAI and ICMR have strengthened (exceeded 0.50) during the recent years and remained stable, while the correlations between Nino 3.4 and ICMR have weakened during the recent years [*Krishna Kumar et al.*, 1999; *Kripalani et al.*, 2001]. It may be noted that the turning points of both 21-year running correlation curves occurred around 1983. The weaker linkage between ENSO and the ISM since 1983 may be due to stronger influence from the North Atlantic to the Indian monsoon in the recent 20 years or so. This aspect was emphasized by *Chang et al.* [2001] suggesting that favorable North Atlantic winter circulation anomalies are responsible for the weakening relationship between ENSO and Indian summer monsoon.

[8] The relationship between the north Atlantic SST anomalies and ICMR has been further quantified using a Canonical Correlation Analysis (CCA) [*Bretherton et al.*, 1992], which is a powerful multivariate statistical technique to find out the coupled climate patterns between two fields. Table 1 shows the main results of the analysis. The canonical correlations of the first three components are 0.665, 0.439 and 0.373 respectively. Three canonical coefficients accounted for about 34% of total variation of ICMR. However, there is no clear relationship between the correlation and the proportion of variance explained by the associated coefficients. Figure S1 of the auxiliary material[1] shows the factor loadings of the canonical coefficients for the SST and rainfall for the first three components. The loadings represent the correlations between the canonical coefficients and the SST or rainfall. The maximum loading of the first mode of SST is observed over NW Atlantic, where significant correlations with ICMR were also observed. The second mode pattern resembles a tripole pattern with positive loading over the central parts of north India and negative loading to north and south. The loading pattern of rainfall shows maximum loading over central and NW India. Thus, the canonical correlation analysis also showed a strong coupling between the SST anomalies over NW Atlantic and monsoon rainfall over the core monsoon zone.

4. Physical Relationships

[9] In this section, we examine the possible physical relationships between the north Atlantic SST anomalies and Indian monsoon rainfall. The analysis showed that the observed SST anomalies are caused by the large scale variations in the Azores High over the North Atlantic. Figure S2 shows the difference of the sea level pressure and surface wind anomalies between the years with positive NWAI and negative NWAI, which suggests that the positive SST anomalies over the NW Atlantic are caused by more intense sub tropical Azores High and associated anomalous anticyclonic flow [*Dugam et al.*, 1997].

[10] Figure 4 (top) shows the spatial pattern of correlations between the NWAI and vector winds at 200 hPa during the JAS season for the period 1976–2005. Statistically significant (at 95% level) correlation vectors are shown as dark winds. It shows positive NWAI is associated with stronger sub tropical anticyclone including the stronger Tibetan anticyclone. Figure S3 shows the spatial pattern of correlations between NWAI and zonal winds at 200 hPa. Positive (negative) correlations are observed over north (south) Europe. It suggests the shifting of the north Atlantic jet stream to northern latitudes due to stronger Azores high over the north Atlantic. Positive NWAI is associated with a dipole structure of circulation anomalies over Europe; cyclonic circulation over SW Europe and an anticyclonic circulation over North Europe. Near the Caspian sea, cyclonic circulation anomalies are also observed. Figure 4 (bottom) shows the spatial pattern of correlations between the NWAI and winds at 850 hPa during the JAS period of 1976–2005. It shows that positive NWAI is associated with stronger cross equatorial flow into Arabian Sea and stronger monsoon westerlies. Positive NWAI is also associated with easterlies over northern plains of India, thus large scale convergence over the monsoon core zone.

[11] Some previous studies have examined the influence of the mid and high latitude system on the break/active phase of the Indian summer monsoon on intraseasonal and interannual time scales [*Raman and Rao*, 1981; *Kripalani et al.*, 1997; *Rajeevan*, 2002; *Yadav*, 2008]. There are known pathways for the North Atlantic circulation anomalies affecting Indian summer monsoon through the Rossby wave train over Europe emanating from North Atlantic and propagating along the Asian Jet stream [*Branstator*, 2002; *Hoskins and Ambrizzi*, 1993]. The recent study of *Ding and Wang* [2005] examined the mid-latitude circulation and its influence on Indian summer monsoon. The study reveals a recurrent circumglobal teleconnection (CGT) pattern in the summertime midlatitude circulation of the Northern Hemisphere. The CGT is accompanied by significant rainfall and surface air temperature anomalies over India and has significant correlations with the Indian summer monsoon (ISM). This study also suggested a wave train that is excited in the jet exit region of the North Atlantic may affect the west central Asian High and, thus the intensity of the Indian summer monsoon. Using rainfall data, they have shown that

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036025.

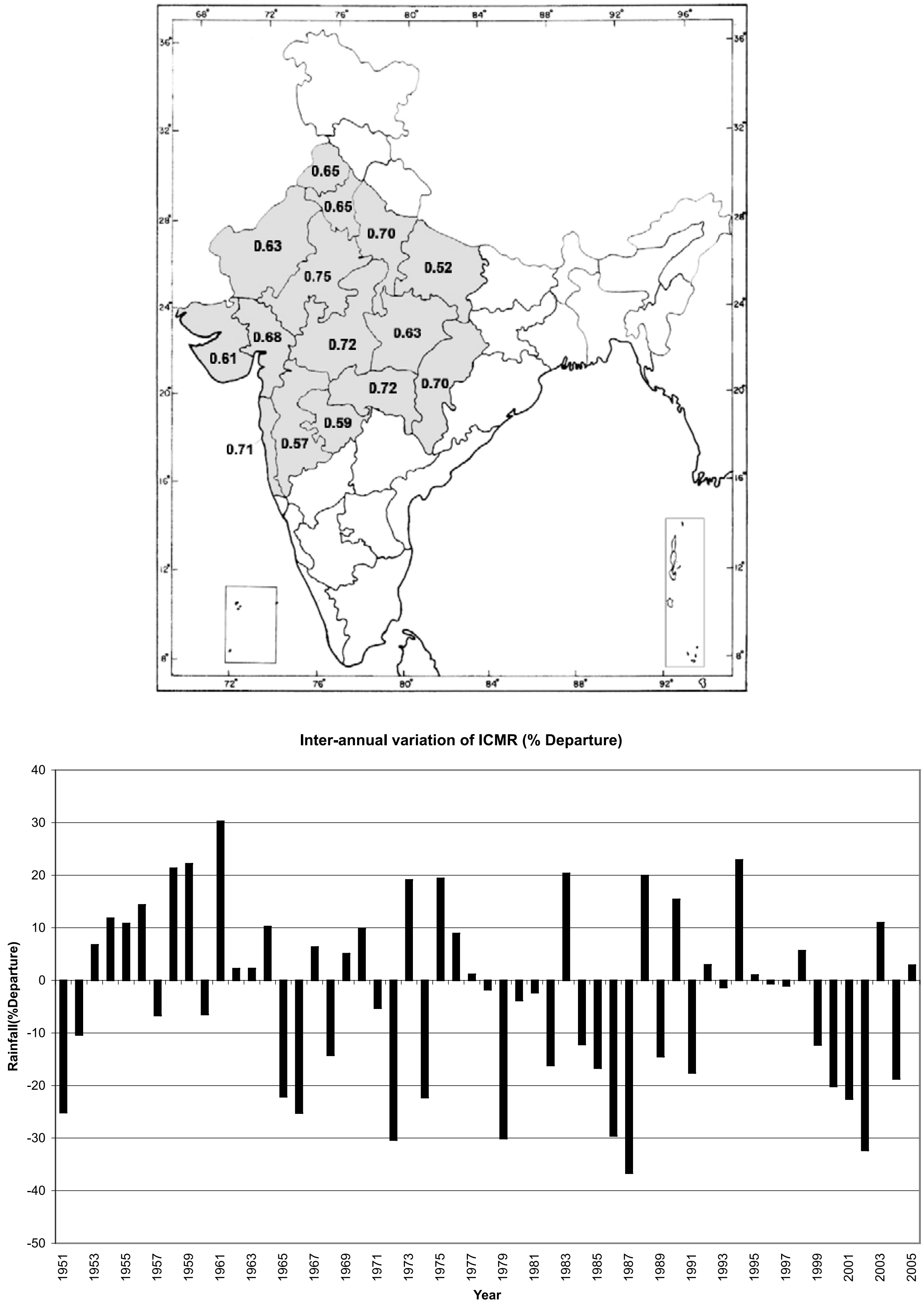

Figure 1. (top) Monsoon Core Region considered for the study and (bottom) Inter-annual variation of Indian Core Monsoon Rainfall (ICMR) (1951–2005) as percentage departure. Mean rainfall = 691 mm and Coefficient of variation: 17%.

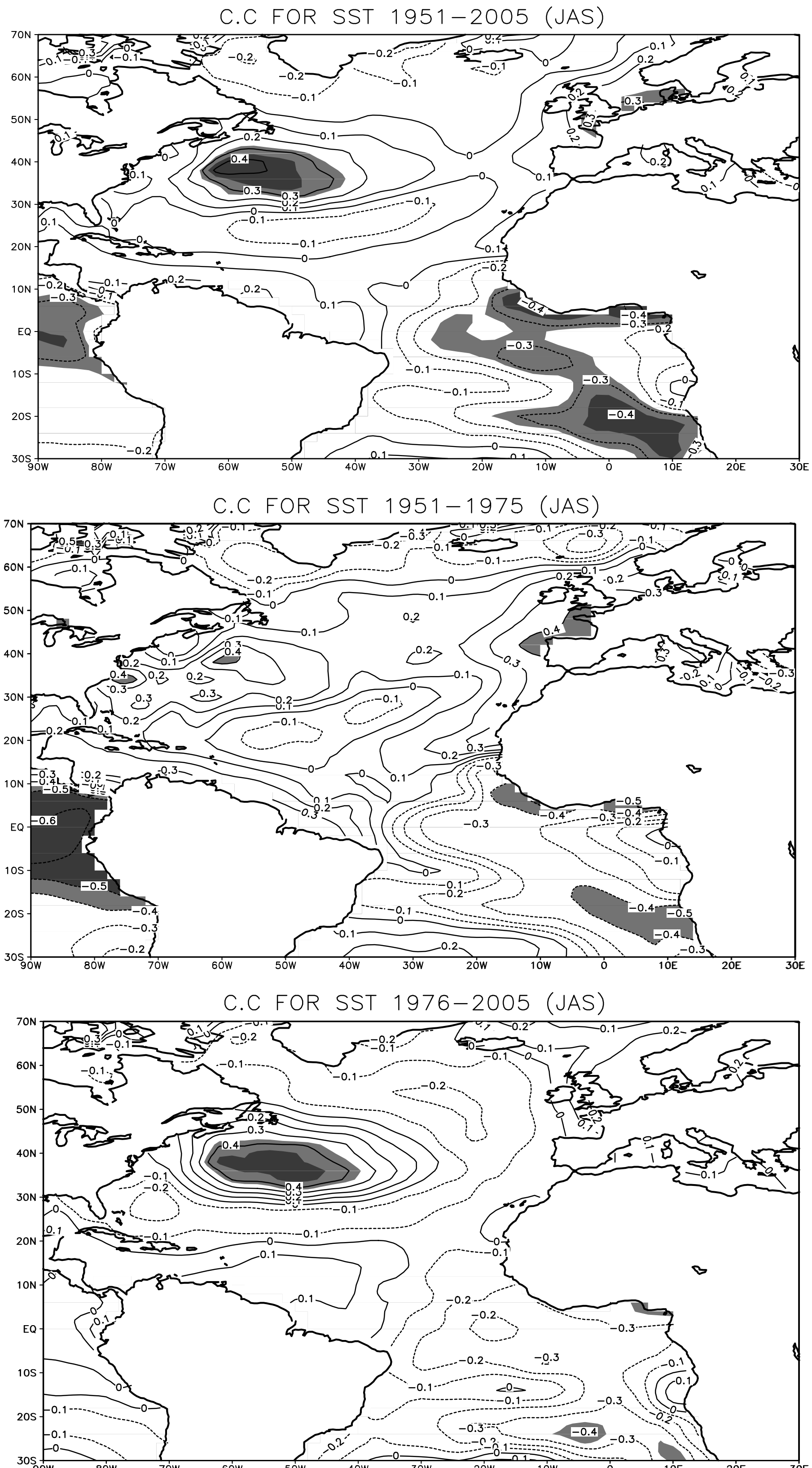

Figure 2. Spatial map of correlation of SST anomalies with ICMR for three different periods, (top) 1951–2005, (middle) 1951–1975 and (bottom) 1976–2005. Correlations significant at 95% (99%) level are shaded light (dark).

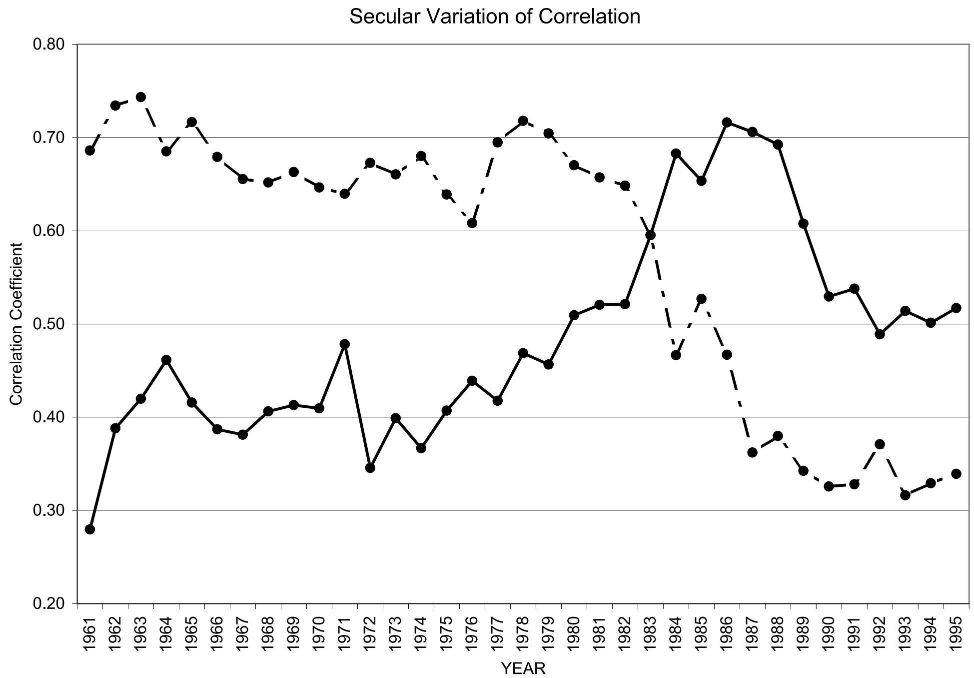

Figure 3. The 21-year running correlations between the SST index and ICMR (continuous line) and between the Nino-3.4 index and ICMR (dashed line). The sign of the correlation between Nino 3.4 and ICMR has been reversed for comparison.

when northwest India and Pakistan experience floods, there is a drought tendency over central-western Europe and a wet tendency in eastern Europe. This feature is clearly observed in Figure 4 (top), the cyclonic circulation anomaly at 200 hPa over central-western Europe and anticyclonic circulation anomaly over eastern Europe, suggesting deficient (excess) rainfall over central-west (east) Europe. The circumglobal teleconnection pattern discussed by *Ding and Wang* [2005] is clearly observed in Figure 4 (top), showing the correlations of NWAI with wind vectors at 200 hPa.

[12] In this study, we have seen the evidence of shifting of the North Atlantic Jet to north Europe during the years with positive NWAI, which is triggered by the upstream disturbances. A Rossby wave train stretching from western Europe to west-central Asia is favoured by the local basic state [*Ding and Wang*, 2005]. Accompanying the wave train, strong stationary wave energy is transported from high latitude to west-central Asia, inducing a secondary anomalous high as observed in Figure 4 (top). Significant anomalous easterlies are also observed over northern parts of India, south of the anomalous sub-tropical high. These easterly anomalies in the upper troposphere reinforce easterly vertical shear over north India. *Ding and Wang* [2005] discuss the role of enhanced vertical easterly shear on monsoon rainfall. The increased shear may act to confine the Rossby wave response to the lower level and produce a stronger Ekman pumping-induced heating and an enhanced meridional heat flux, both of which would increase the dynamic instability of the atmosphere and thus increase monsoon rainfall over the core region.

5. Summary and Conclusions

[13] The present study revealed statistically significant correlations between the SST anomalies over NW Atlantic, which are caused by the changes in the position and strength of the Azores High. During the above normal monsoon years, Azores high and Aleutian low become stronger and the North Atlantic Jet moves northwards. Further it has been documented that the changes in the North Atlantic Jet stream influence monsoon rainfall over the monsoon core region through the circumglobal teleconnection across central Asia. Rossby wave train from the exit region of the North Atlantic Jet makes the sub tropical high including the Tibetan high much stronger. The anomalous easterlies south of the subtropical high increases the easterly vertical shear over north India, which enhance the dynamic instability of the atmosphere and rainfall over the monsoon core region.

[14] Thus, the north Atlantic teleconnection pattern is partly accountable for the inter-annual variation of southwest monsoon rainfall over the monsoon core region and may be considered for prediction of Indian monsoon rainfall along with the information on ENSO and Indian Ocean. Since the present study discussed only the simultaneous relationships, more research work is required to examine possible precursors of this relationship and use them as predictors in the empirical seasonal forecast models.

Table 1. Results of the Canonical Correlation Analysis: Canonical Correlation, and Percent of Variance of SST and Rainfall[a]

Canonical Component	Canonical Correlation	Percent of Variance (SST)	Percent of Variance (Rainfall)
1	0.665	12.6	13.7
2	0.439	7.5	16.0
3	0.373	13.6	4.0

[a]Period of Canonical Correlation Analysis: 1951–2005.

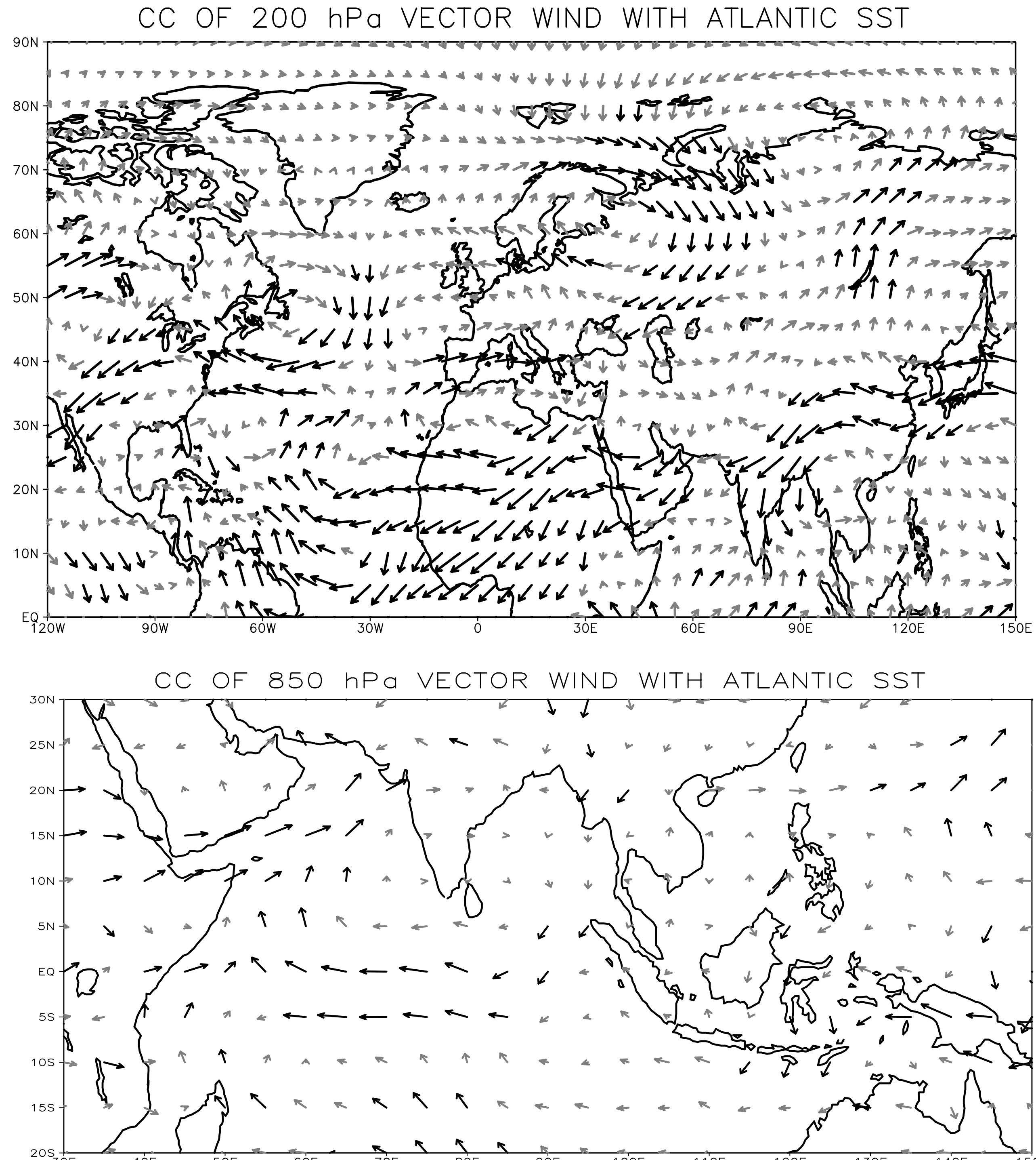

Figure 4. Spatial pattern of correlation between NWAI and vector winds at (top) 200 hPa and at (bottom) 850 hPa. Period: 1976–2005. Statistically significant correlations (95% level) are shown in dark.

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