A physical mechanism for North Atlantic SST influence on the Indian summer monsoon

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[1] A link between the Atlantic Multidecadal Oscillation (AMO) and multidecadal variability of the Indian summer monsoon rainfall is unraveled and a long sought physical mechanism linking Atlantic climate and monsoon has been identified. The AMO produces persistent weakening (strengthening) of the meridional gradient of tropospheric temperature (TT) by setting up negative (positive) TT anomaly over Eurasia during northern late summer/autumn resulting in early (late) withdrawal of the south west monsoon and persistent decrease (increase) of seasonal monsoon rainfall. On inter–annual time scales, strong North Atlantic Oscillation (NAO) or North Annular mode (NAM) influences the monsoon by producing similar TT anomaly over Eurasia. The AMO achieves the interdecadal modulation of the monsoon by modulating the frequency of occurrence of strong NAO/NAM events. This mechanism also provides a basis for explaining the observed teleconnection between North Atlantic temperature and the Asian monsoon in paleoclimatic proxies. **Citation:** Goswami, B. N., M. S. Madhusoodanan, C. P. Neema, and D. Sengupta (2006), A physical mechanism for North Atlantic SST influence on the Indian summer monsoon, *Geophys. Res. Lett.*, *33*, L02706, doi:10.1029/2005GL024803.

1. Introduction

[2] A link between cold episodes in the North Atlantic and weakened Asian monsoon during the last glacial period associated with the so called Dansgaard/Oeschger and Heinrich events [*Burns et al.*, 2003] as well as during mid and late Holocene [*Gupta et al.*, 2003] have been noted. Other studies [*Srivastava et al.*, 2002; *Chang et al.*, 2001; *Rajeevan*, 2002] also indicate links between North Atlantic and Indian summer monsoon on inter–annual and decadal time scales. Here we identify a close relationship between interdecadal variability of North Atlantic sea surface temperature (SST) and that of the Indian monsoon rainfall and discover a physical mechanism linking the North Atlantic SST and Indian monsoon rainfall that has been elusive so far.

[3] The June–September (JJAS) all India monsoon rainfall (AIR) [*Parthasarathy et al.*, 1995] goes through alternating interdecadal swings of above and below normal rainfall each lasting for about three decades [*Kripalani et al.*, 1997; *Krishnamurthy and Goswami*, 2000; *Goswami*, 2005]. The quasi–60 year periodicity is also seen in proxies of monsoon rainfall derived from Arabian Sea sediments [*Agnihotri et al.*, 2002] and in rainfall over east China [*Goswami*, 2005]. As higher frequency of occurrence of droughts (floods) are associated with the negative (positive) interdecadal phases [*Kripalani and Kulkarni*, 1997], prediction of the interdecadal swings could be of great value for agricultural planning. Accurate prediction of these swings would, however, require better understanding of causes of the variability. Some studies [*Agnihotri et al.*, 2002; *Mehta and Lau*, 1997] proposed that solar variations drive this interdecadal oscillation of the Asian monsoon. However, the mechanism remains unconvincing as direct radiative forcing associated with interdecadal solar variability is rather small. An alternative mechanism was proposed by *Krishnamurthy and Goswami* [2000] from analysis of long term data on sea level pressure, SST and AIR where they showed a strong link between the interdecadal variability of the Indian summer monsoon and that of amplitude modulation of the El Niño and Southern Oscillation (ENSO). This study proposed that the interdecadal variability of the Indian monsoon is a manifestation of an internal oscillation of the coupled ocean atmosphere system. The present study reinforces this paradigm by demonstrating that the quasi–60 year oscillation of the monsoon rainfall varies coherently not only with ENSO, but also with the multidecadal variability of SST over the North Atlantic basin. Further, an atmospheric bridge through which North Atlantic SST influences the monsoon rainfall is unraveled.

2. Data and Methods

[4] The AIR data used in this study is based on rainfall observations at 306 raingauge stations of the India Meteorological Department (IMD) uniformly distributed over India. The time series of JJAS averaged rainfall has been constructed by *Parthasarathy et al.* [1995] and updated to cover the years between 1871–2003. The HadSLP1 sea level pressure (SLP) data which is an update of the GMSLP2 data [*Basnett and Parker*, 1997] has been used to construct the North Atlantic Oscillation (NAO) index. The correlation between the winter NAO index [*Hurrell*, 1996] and subsequent AIR is statistically insignificant ($r = 0.1$, between 1871 and 1998). Also the physical mechanism through which the winter NAO influences the subsequent summer monsoon rainfall is unclear. We define a summer NAO index as JJAS mean of difference between normalized SLP anomalies over two 5×5 degree boxes, one in the north centred around 20°W, 65°N (close to Iceland) and one in the south around 30°W, 40°N. The southern point is chosen to be over the region where the SLP has largest variability during northern summer [*Portis et al.*, 2001]. It is interesting to note that the summer NAO index has a weak but statistically significant simultaneous

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correlation with AIR (r = 0.25 between 1871 and 1998). For constructing the Atlantic Multidecadal Oscillation (AMO) index, the global SST analysis of *Kaplan et al.* [1998] is used. The circulation data is taken from NCEP/NCAR reanalysis data set [*Kalnay et al.*, 1996]. Daily temperature and winds at different atmospheric levels between January 1948 and December 2003 have been used. The tropospheric temperature (TT) is defined as vertically averaged temperature between 200 hPa and 600 hPa.

3. AMO, Indian Monsoon and El Niño

[5] SST over the North Atlantic basin has a basin wide oscillation with period around 65–80 year, often referred to as the Atlantic Multidecadal Oscillation (AMO) [*Kerr*, 2000]. Warm AMO phases occurred during 1860–1890 and 1925–1960 while cool phases occurred during 1895–1925 and 1965–1990. The North Atlantic SST contributed strongly to the 65–70 year oscillation of the detrended global mean surface temperature found by *Schlesinger and Ramankutty* [1994], and appears to be related to the AMO. *Delworth and Mann* [2000] found an approximate 70 year oscillation in proxy based reconstruction of surface temperature for 330 years as well as in a multi–century integration of a coupled ocean–atmosphere general circulation model (CGCM). Simulated oscillation involved fluctuations of the thermohaline circulation, and the SST anomalies over the North Atlantic resembled the observed anomalies indicating that the AMO may be an internal mode of oscillation of the coupled ocean–atmosphere system. The AMO appears to be the pacemaker of northern hemispheric climate. Strong correlation between AMO and many climate parameters of the northern hemisphere, such as the rainfall over Florida and Mississippi river discharge, have been noted [*Enfield et al.*, 2001]. During AMO warmings most of the United States sees less than normal rainfall including the Midwest droughts in the 1930s and 1950s [*Enfield et al.*, 2001]. The AMO is represented by passing the June–September mean SST anomaly averaged over the north Atlantic (0°–70°N, 90°W–20°E) through a 9–year running mean filter twice, and is shown together with similarly low-pass filtered AIR (Figure 1). Although there are some quantitative differences between the two low–pass filtered time series, all the transitions from positive to negative or from negative to positive anomalies of AIR match well with that of the AMO and the two low-pass filtered time series are significantly correlated. It may be also noted that the low-pass filtered

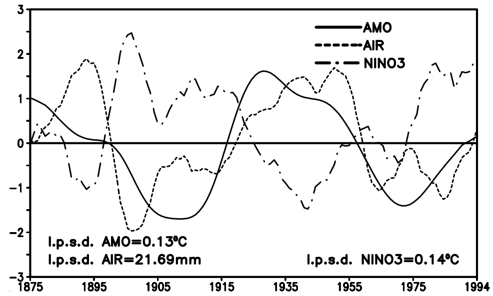

Figure 1. Interdecadal variability of AIR, JJAS AMO and JJAS Niño3 SST. Each time series is normalized by its own low-pass filtered standard deviation (l.p.s.d.). Unit of AMO and Niño3 SST is °C while that for AIR is mm.

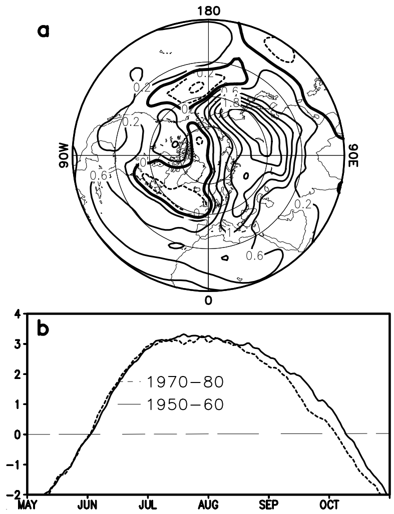

Figure 2. (a) Difference of composite TT (°C) for 11 years of warm (1950–1960) and cold (1970–1980) interdecadal period averaged over 1 July to 30 September. (b) Daily evolution of ΔTT (see text for definition) composited for the 11 year of warm and 11 year of cold interdecadal periods.

JJAS Niño3 SST is inversely related to the AMO as well as the AIR. Such coherent interdecadal variability of amplitude of El Niño and AMO has not been highlighted so far. A regression of AMO index shown in Figure 1 with JJAS SST anomalies elsewhere shows (see Figure S1[1]) a significant signal over the Niño3 region. This indicates that the coupled ocean–atmosphere oscillation that generates the AMO also seems to modulate the amplitude of El Niño as well as the Indian monsoon.

4. The Teleconnection Mechanism

[6] How does the AMO influence the monsoon rainfall? The onset and withdrawal of the Indian summer monsoon and the seasonal rainfall are governed by the meridional gradient of the tropospheric heating that may be represented by the meridional gradient of tropospheric temperature (ΔTT) [*Goswami and Xavier*, 2005]. If ΔTT is defined as the difference of TT vertically integrated between 200 hPa and 600 hPa between a north box (30°E–100°E, 10°N–35°N) and a south box (30°E–100°E, 15°S–10°N), the onset and withdrawal of the southwest monsoon are determined by the crossing of ΔTT from negative to positive and from positive to negative respectively [*Goswami and Xavier*, 2005]. The length of the monsoon rainy season is, hence, determined by the change of sign of ΔTT. Further, the area under the positive ΔTT is strongly correlated with the seasonal rainfall total (see Figure S2). The AMO could influence monsoon season rainfall if it could change the ΔTT significantly. Difference between TT for the period between 1 July and 30 September composited for 11 years during a warm AMO phase (1950–1960) and for 11 years of a cold AMO phase (1970–1980) is shown in Figure 2a using NCEP/NCAR reanalysis data. A warm AMO phase is associated with a large scale positive TT anomaly over

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024803.

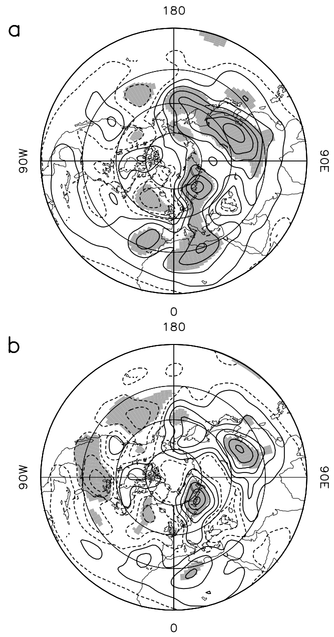

Figure 3. (a) Same as Figure 2a but for composites of years with strong (>1.25 s.d., 1953, 54, 61, 67, 74, 88) and weak (<−1.25 s.d., 1957, 58, 71, 76, 86, 90) JJAS NAO index. (b) Same as Figure 3a but for non−ENSO strong (1953, 61, 67, 74) and non−ENSO weak (1958, 71, 86, 90) JJAS NAO index. Positive (negative) countours are solid (dashed) with minimum being 0.1 (−0.1) and contour interval 0.3. Shading indicates 90% confidence regions.

Eurasia compared to a cold AMO phase (Figure 2a), thereby increasing the meridional gradient of TT, delaying monsoon withdrawal and enhancing the monsoon rainfall. This is further illustrated in Figure 2b where the composited time evolution of ΔTT during a warm and a cold phase of AMO are shown. The area under the positive ΔTT is systematically lower in a cold AMO phase compared to a warm AMO phase, the largest contribution coming from the withdrawal phase of the monsoon. Significant large scale wind anomalies associated with this interdecadal variability are in geostrophic balance and have an equivalent barotropic vertical structure (see Figure S3). How does the low frequency variability of the North Atlantic SST or the AMO result in the TT variability with large scale negative (positive) anomaly over Eurasia? The North Atlantic Oscillation provides the required atmospheric bridge. Probably the most important mode of variability in the northern hemisphere, NAO simply measures the strength of the westerly winds blowing across the North Atlantic Ocean between 40°N and 60°N. Although originally defined in terms of a regional seesaw of sea level pressure between the 'Icelandic low' and 'Azores high', it is not a regional phenomenon but has hemisphere extent [*Wallace*, 2000; *Hurrell*, 1996]. NAO is characterized by strong month−to−month and year−to−year variability but also has some decadal trend or interdecadal variability [*Ostermeier and Wallace*, 2003; *Hurrell*, 1995]. While the basic high frequency component of NAO may be of internal atmospheric origin, the low frequency interdecadal part of NAO variability may be modulated by the low frequency SST variability that arises from an internal coupled ocean−atmosphere oscillation [*Delworth and Mann*, 2000]. As NAO is known to be associated with significant surface temperature anomalies over Eurasia [*Hurrell*, 1995] and since the vertical structure of the NAO/NAM anomalies is known to be equivalent barotropic [*Thompson and Wallace*, 1998], we may expect NAO also to be associated with TT anomaly over Eurasia.

[7] To see how strong or weak summer NAO could influence the Indian monsoon, composite of TT averaged between 1 July and 30 September corresponding to strong positive (>1.25 s.d.) and negative (<−1.25 s.d.) JJAS NAO index were created. The difference between the positive and negative composites (Figure 3a) shows large scale positive TT anomaly over Eurasia with a maximum over China and negative TT anomaly over northern Pacific and north−western United States during a positive NAO phase and bears close resemblance with the pattern of TT anomalies associated with positive AMO phase (Figure 2a). Hemispheric modulation of the winds by the NAO and associated change in the storm tracks [*Rogers*, 1990] are responsible for the TT anomalies over Eurasia. To examine whether the composites used in Figure 3a could have been biased by ENSO influence, difference of TT anomaly between 1 July and 30 September for non−ENSO strong and weak JJAS NAO index were constructed (Figure 3b). It is clear that even without ENSO influence, summer NAO introduces significant TT anomaly over northern India and southern Eurasia. Such TT anomalies weaken the meridional gradient of TT over the Indian monsoon region, force early withdrawal and lead to decreased monsoon rainfall during a negative NAO phase. The area under positive ΔTT is significantly reduced during a negative NAO phase compared to that during a positive NAO phase corresponding to lower than normal monsoon rainfall. A mechanism is, thus, identified through which strong NAO events influence seasonal monsoon rainfall. However, weak or near normal NAO events cannot produce large enough TT anomaly over Eurasia and hence cannot introduce significant gradient of TT to influence the monsoon rainfall. This is consistent with the observation that correlation between AIR and an NAO index, all years taken together, is rather weak.

5. Conclusion

[8] Some empirical association between Indian monsoon variability and climate over the North Atlantic (SST, surface air temperature, surface pressure and OLR) have been noted for some time. However, a physical mechanism for the teleconnection has been elusive. For the first time, a physical mechanism for this teleconnection has been identified here. The fundamental link between the North Atlantic and the Indian summer monsoon is through the NAO. Strong negative (positive) NAO/NAM events, through hemispheric change in winds and storm tracks, lead to TT anomalies over Eurasia. These anomalies decrease (increase) meridional gradient of TT resulting in below (above) normal monsoon rainfall. As seen from Figure 4, the summer NAO is modulated by the AMO, with positive (negative) AMO phase being characterized by tendency of the summer NAO being above (below) normal and increasing the frequency of strong positive (negative) events. By modulating the NAO to a persistently

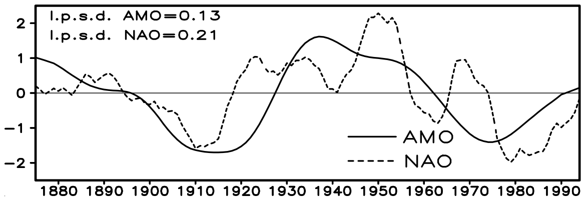

Figure 4. Low-pass filtered (two successive applications of 9-year running mean) JJAS NAO index (dotted) together with that of JJAS AMO index (solid). Both time series are normalized by their own low-pass filtered standard deviation.

higher (lower) than normal state and hence higher occurrence of strong positive (negative) NAO events, the AMO forces the interdecadal variability of the Indian monsoon. The ocean–atmosphere coupling likely to be associated with the AMO [*Delworth and Mann*, 2000] indicates that the interdecadal variability of the Indian monsoon is also an integral part of this ocean–atmosphere oscillation. This provides optimism for high potential predictability of the interdecadal swings of the Indian summer monsoon rainfall. On inter–annual time scales, El Niño influences Indian monsoon through TT anomalies over Eurasia via stationary waves set up by tropical heating over the central Pacific [*Goswami and Xavier*, 2005]. The mechanism for teleconnection on interdecadal time scale is again through TT anomalies over Eurasia, but via stationary waves set up by extratropical forcing. There appear to be two teleconnection pathways through which Indian summer monsoon is modulated on interdecadal timescale. A tropical teleconnection mechanism was proposed for the interdecadal modulation of the Indian monsoon by ENSO by *Krishnamurthy and Goswami* [2000] that involves shift of the Walker circulation influencing the regional monsoon Hadley circulation. The other is an extratropical teleconnection mechanism in which AMO modulates the Indian monsoon through persistent TT anomalies over Eurasia. A positive AMO produces stronger monsoon by producing positive TT anomaly over Eurasia. It is also associated with enhanced La Nina type Pacific SST anomalies that induces stronger regional monsoon Hadley circulation and stronger monsoon. Thus, these two teleconnection mechanisms are complementary in modulating the monsoon.

[9] Since the Indian monsoon is driven primarily by meridional gradient of deep tropospheric heating, surface temperature gradient between Eurasia and north Indian Ocean is inadequate to explain the observed link between North Atlantic and Indian monsoon seen in some paleoclimatic proxies [*Burns et al.*, 2003; *Gupta et al.*, 2003]. The mechanism identified here provides the necessary mechanism for this connection on longer time scale as well.

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