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ABSTRACT

Since the 1970s, the inverse relationship between the Indian monsoon rainfall and the El Niño–Southern Oscillation (ENSO) has weakened considerably. The cause for this breakdown is shown to be most likely the strengthening and poleward shift of the jet stream over the North Atlantic. These changes have led to the recent development of a significant correlation between wintertime western European surface air temperatures and the ensuing monsoon rainfall. This western Europe winter signal extended eastward over most of northern Eurasia and remained evident in spring, such that the effect of the resulting meridional temperature contrast was able to disrupt the influence of ENSO on the monsoon.

1. Introduction

The long-recognized negative correlation between Indian monsoon rainfall and ENSO (e.g., Webster and Palmer 1997), in which a weak (strong) monsoon is related to a warm (cold) event through an anomalous Walker cell driven by tropical east Pacific sea surface temperature (SST) anomalies, has weakened rapidly since the late 1970s (Kumar et al. 1999, hereinafter K99). This weakened relationship is defined by the correlation between June and September all-India rainfall (Parthasarathy et al. 1995) and Niño-3 (5°S–5°N, 150°–90°W) SST (bottom curve of Fig. 1, which is reproduced from K99). This correlation has been consistently around the 1% significance level from 1856 until the 1970s (Fig. 1 is truncated at left). Webster and Palmer (1997) related this interruption of the ENSO–monsoon relationship to the chaotic nature of the monsoon; K99 viewed the rapid weakening of the correlation as systematic and proposed that it may be due to changes in the Pacific Walker circulation and the warming of the Eurasian continent. In this paper, we address these issues and show that the weakening relationship is more likely related to recent circulation changes over the North Atlantic.

2. Data

The data used are the SST, the surface air temperature (SAT), wind, and velocity potential fields of the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis for 1949–98 (Kalnay et al. 1996). Also, the Department of Energy (DOE) SAT data are used for the period of 1856–1990 (Jones 1994). The spatial coverage of the DOE data is variable. Over the Eurasian continent, the best coverage is over 50°–60°N, 0°–20°E, which turns out to be an important area and shall be called western Europe (wE). This area contains nine $5° \times 5°$ points that have data available continuously for all years. This dataset overlaps with the reanalysis data between 1949 and 1990, during which the correlation between the two datasets for SAT averaged over the wE area is 0.97 during winter (December–February) and 0.95 during spring (March–May).

3. Analysis

K99 explained the weakened ENSO–monsoon relationship based on the observation that after the late 1970s the composite Walker circulation during El Niño summers shifted southeastward. The upward branch of the Walker cell moved from the central Pacific to near South America and the downward branch moved from the Indian Ocean to the ''maritime continent'' and Australia (Figs. 2a,b). However, the differences between warm- and cold-event composites for the two periods (Figs. 2e,f) have very similar patterns. This is because the composite Walker cells of the cold events (Figs. 2c, d) are shifted northwestward from 1950–77 to 1978–98, moving the upward branch closer to India. The shifts in both warm and cold events are consistent with the increase of the decadal-mean tropical east Pacific SST

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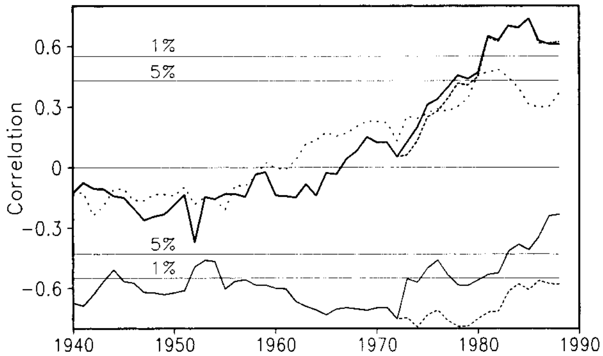

FIG. 1. Correlation (based on a 21-yr sliding window) between Indian summer monsoon rainfall and summer Niño-3 SST (thin solid), winter western European SAT (thick solid), and winter central Eurasian SAT (dotted). Dashed lines are the result of removing 1983 and 1997. The 1% and 5% significance levels are indicated as horizontal lines.

in the late 1970s (Trenberth and Hurrell 1994), which results in no shift of the *within-period* anomalous circulation. These results[1] suggest that the interdecadal change of the Walker cells does not play an important role.

K99 also related the weakened ENSO–monsoon relationship to a change in land–sea temperature contrasts that drive the monsoon. Since it is expected that monsoon rainfall will be decreased by El Niño and increased by warm winter–spring Eurasian surface temperature, the generally warmer Eurasian surface in recent decades may give rise to a wetter monsoon even in the presence of an El Niño. This was indeed observed in the composite of El Niño events during 1981–97 by K99, who argued that the effect of Eurasian surface temperature has dominated that of ENSO during recent decades. However, this implies that during cold events the ENSO effect should be stronger. Alternatively, *relatively* (within 1978–97) cold Eurasian winters should exert a weaker influence. The net result is that the correlation between ENSO and monsoon rainfall within the period of 1978–98 should not be altered much.

For 1950–77, the correlation between Indian monsoon rainfall and the preceding winter Eurasian SATs (Fig. 3a) is weak over the entire domain. This is in marked contrast with the correlation for the 1978–98 winter (Fig. 3b) where positive correlation (5% level) occurs over a large area of western Eurasia, with the maximum centered near wE. This is consistent with Bamzai and Shukla's (1999) results in which the only significant inverse correlation between the 1973–94 winter snow cover and the subsequent Indian summer monsoon rainfall occurred over western Europe. For the 1950–77 spring, the correlation (Fig. 3c) continues to be very weak over the midlatitudes, but there is significant positive correlation over localized subtropical areas around northern India and the Himalaya. These positive correlations seem to support the hypothesis that snow cover over Tibet and the Himalaya influence the strength of the monsoon (Li and Yanai 1996). However, this is not true for 1978–98 spring (Fig. 3d), when the correlation in this area is weak, with isolated negative regions. The area of significant positive correlation around wE shrinks drastically from that of winter. The correlation during the 1978–98 spring over most of midlatitude Eurasia outside of Euro-Russia remains weakly positive, however. The pattern in Fig. 3d suggests a possible continent-scale meridional thermal contrast effect (across about 30°N) on the ensuing monsoon.

[1] In Fig. 2, the threshold for warm and cold events is 0.7 times the within-period standard deviation. All patterns remain basically unchanged if K99's threshold of one long-term standard deviation is used.

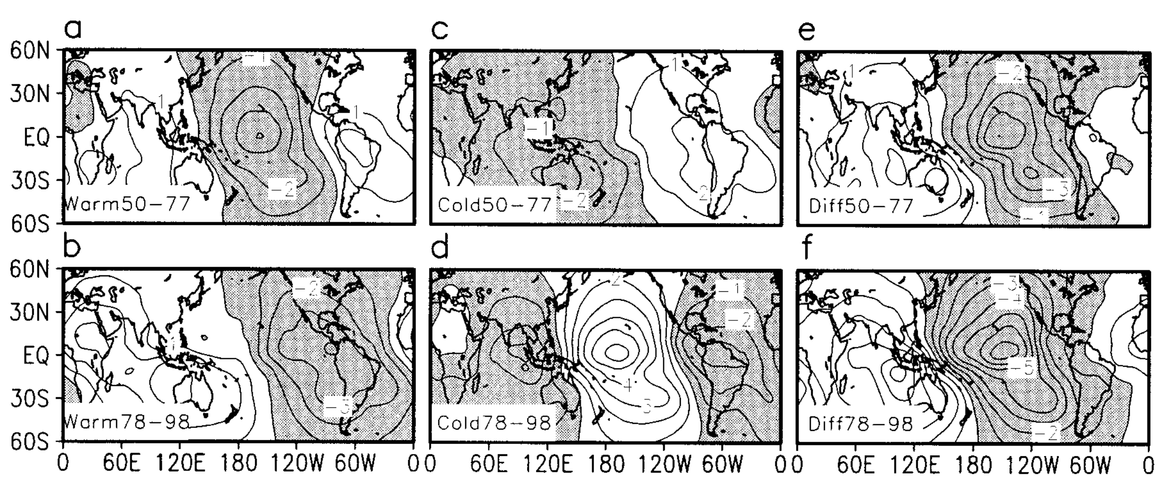

FIG. 2. Composites of northern summer velocity potential at 200 hPa for Niño-3 warm events during (a) 1950–77 (8 cases) and (b) 1978–98 (5 cases), for cold events during (c) 1950–77 (5 cases) and (d) 1978–98 (6 cases), and differences of warm years minus cold years for (e) 1950–77 and (f) 1978–98. The contour interval is 1×10^6 m^2 s^{-1}, and the negative values are shaded. The warm and cold events were identified by SST anomalies during northern autumn and winter exceeding 0.7 std dev within each interdecadal period.

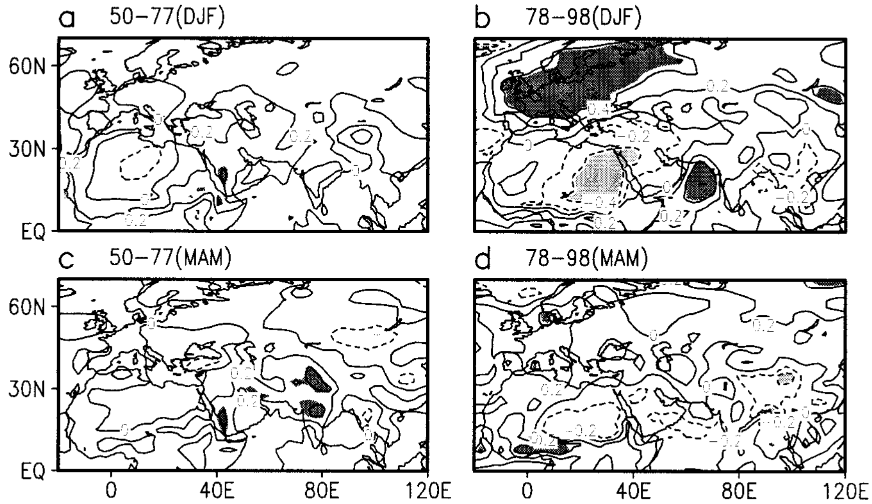

FIG. 3. Correlation between Indian summer monsoon rainfall and winter SAT for (a) 1950–77 and (b) 1978–98, and spring surface temperature for (c) 1950–77 and (d) 1978–98. The contour interval is 0.2 and significant (5% level) correlations are shaded (positive: dark, negative: light).

The correlation between winter wE SAT and the subsequent Indian monsoon rainfall had been small until the most recent decades, when it became significantly positive (above the 1% level) for the first time in more than a century (Fig. 1). This drastic change seems to occur around the time of the weakening of the monsoon–ENSO relationship. Both changes suggest that influences on the monsoon underwent a significant decadal-scale change. The composite preceding winter 500-hPa streamfunction differences between wet and dry monsoons during 1950–77 (Fig. 4a) exhibit an organized Pacific–North America (PNA) teleconnection pattern, which is indicative of the strong relationship with ENSO. During 1978–98 (Fig. 4b), the PNA pattern is still visible over the Pacific, but it is nearly absent over North America. During these latter decades, the most organized pattern is a pair of zonally stretched anomalous cyclone and anticyclone circulations that span the entire North Atlantic. Over North America, this circulation pattern is almost opposite of the PNA. The pattern defines an anomalous westerly jet stream extending from northeast North America to northwest Eurasia during the winters preceding a wet Indian monsoon. Therefore, during these winters the jet stream is shifted to a more northerly location, which gives rise to an anomalously warm midlatitude Eurasia with less storm activity (therefore less snow cover or higher SAT). This would be a favorable condition for a subsequent wet Indian monsoon. Since the largest variation of the storm track is located in western Europe, the strongest signal

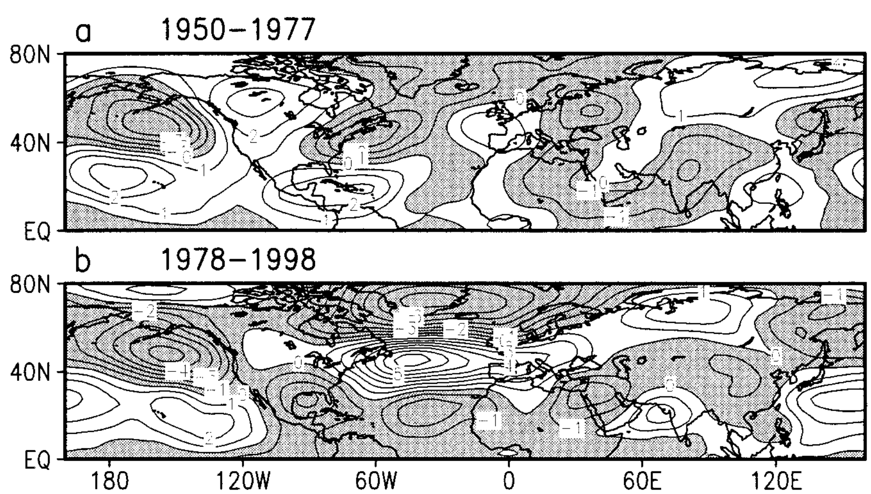

FIG. 4. The 500-hPa streamfunction difference between summer Indian monsoon wet years and dry years for (a) 1950–77 and (b) 1978–98 (contour interval 1×10^6 m^2 s^{-1}). Negative values are shaded. The wet and dry years were identified by monsoon rainfall anomalies exceeding one std dev.

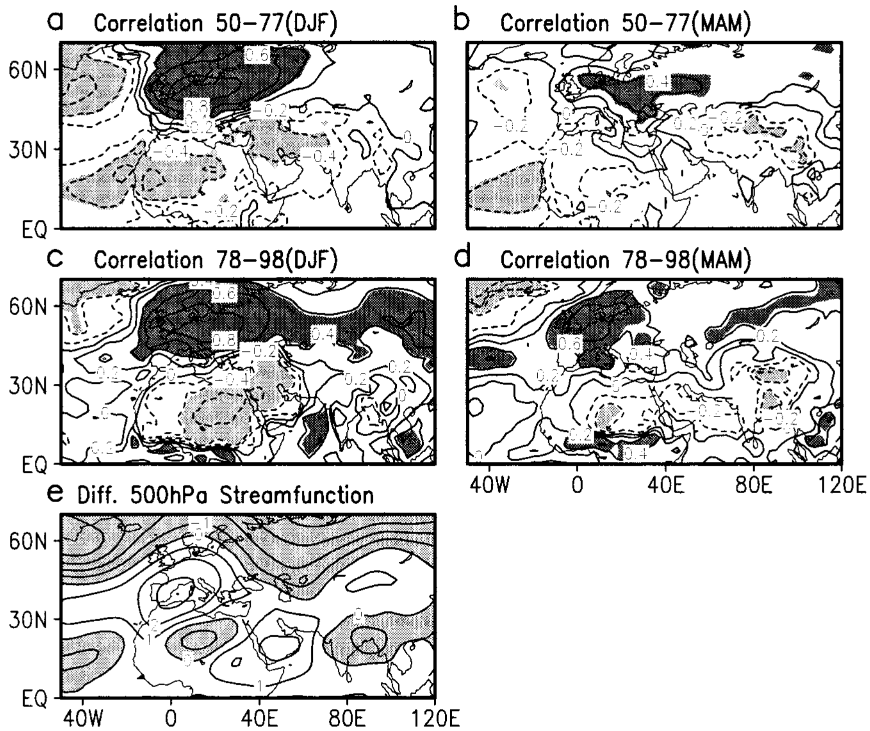

FIG. 5. Distribution of correlations between winter western European SAT index and the 1950–77 (a) winter and (b) spring global SAT, and the 1978–98 (c) winter and (d) spring global SAT. Correlations significant at 5% and above are shaded dark for positive values and light for negative values (contour interval 0.2). (e) The 500-hPa streamfunction difference between the 1978–98 and 1950–77 periods (contour interval is 1×10^6 m^2 s^{-1}; negative values are shaded.)

of the winter SAT–monsoon rainfall correlation during 1978–98 should occur there, as indicated in Fig. 3b.

To understand the recent increased influence of the Eurasian continent on the monsoon rainfall, the winter wE SAT index is used to produce correlation maps with both the winter and spring SAT fields. The largest difference between the two decadal periods occurs in winter, during which significant positive correlations are confined to western Europe during 1950–77 (Fig. 5a) but extend across most of Eurasia during 1978–98 (Fig. 5c). Furthermore, during 1950–77 the winter wE SAT influence decreased rapidly during spring (Fig. 5b), but during 1978–98 the broad winter wE SAT influence persisted into spring across a large region of Eurasia (Fig. 5d). These results are consistent with the interpretation that in 1978–98 western Europe is the ‘‘gateway’’ for winter storm anomalies that affect the Eurasian SAT and the subsequent monsoon. However, the reason for the change in relationships over the most recent decades must still be identified.

The trend of the Eurasia-induced thermal contrast effect on the monsoon rainfall may be seen from the 21-yr sliding correlation between the monsoon rainfall and the preceding winter SAT averaged over the area 40°–70°N, 50°–95°E, hereinafter referred to as central Eurasia. The eastern boundary of 95°E is selected because of a data-sparse area between 100° and 110°E. This correlation (dotted line in Fig. 1) and the very similar correlation for spring (not shown) also become increasingly positive in recent decades. However, the correlation remains below the 5% level, apparently because the strong winter wE signal has spread over the much larger central Eurasian region. This result also indicates that the Eurasian meridional thermal contrast effect on the monsoon rainfall emerges only during recent decades.

The difference between winter mean 500-hPa streamfunction during 1978–98 and during 1950–1977 (Fig. 5e) reveals two wave patterns. A long wave is found over northern latitudes with trough axes over the Atlantic and near 60°E, and a short-wave teleconnection pattern exists across northern Africa and southern Asia. Therefore, westerlies across the North Atlantic turn northeastward toward western Europe, which is a noted feature of the positive phase of the North Atlantic oscillation (NAO; Hurrell 1995). The NAO may be viewed as a regional manifestation of the zonally symmetric Arctic oscillation (AO; Thompson and Wallace 1998), and the positive phase has been unusually dominant over recent decades. The short-wave teleconnection exhibits a down-shear tilt so that its momentum transport favors the strengthened mean westerlies to the north. This is consistent with an anomalous storm track (Rogers 1997) and the eastward extension of correlation between monsoon rainfall and wE winter SAT during 1978–98. The gradient of the anomalous 500-hPa streamfunction in northern Eurasia indicates a weakened jet between 40° and 60°E, which then strengthens farther downstream. This variation may explain the weakening of the wE signal between 40° and 60°E and the increase farther east (Figs. 5c,d) as due to changes of the baroclinic conditions for storm development. Thus, it appears that the stronger influence of the Eurasia surface temperature on the interannual variation of the Indian monsoon in the most recent decades may be caused by the strengthening positive phase of NAO/AO and associated jet stream/storm track patterns over the North Atlantic and northern Eurasia.

4. Concluding remarks

We have shown that the weakening of the ENSO–monsoon rainfall relationship is most likely due to the changes in Atlantic circulation regimes during recent decades. It may be noted that this weakening is mostly due to the summer warm events of 1983 and, to a lesser extent, 1997 (1997 contributes only to the last two data points in Fig. 1). For both years, the influence of a warm Eurasian surface opposes the effect of a warm ENSO event, with 1983 having the highest positive NAO index in the twentieth century. If these two years are removed (dashed lines in Fig. 1), the ENSO correlation for the recent decades will return to the high (1%) level. However, there is little influence on the correlation of the winter wE SAT with the monsoon rainfall. Thus, the effects of circulation changes over the North Atlantic in recent decades are robust and the disruption of the ENSO–monsoon rainfall relationship is probably not accidental.

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