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Precipitation variability over the South Asian monsoon heat low and associated teleconnections

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[1] The present study examines the precipitation variability over the South Asian monsoon heat low region and associated teleconnections using high resolution (T106L31) climate simulations performed with the ECHAM5 model. It is found that an intensification of the heat low in response to enhanced precipitation/convection over northwestern India-Pakistan (NWIP) can induce large-scale circulation anomalies that resemble the northern summer circumglobal teleconnection (CGT) wave-like pattern extending well into the Asian monsoon region. Accordingly the wave-like response to rainfall increase over the heat low region is associated with anomalous ascent over northern China and descent over the South China Sea. Additionally, small but statistically significant lead-lag correlations between the heat low and precipitation over northern China further suggest that the detected signal pertains to the true features of the process. On the other hand, suppressed convection and rainfall over the heat low region do not reveal any significant large-scale circulation anomalies. **Citation:** Saeed, S., W. A. Müller, S. Hagemann, D. Jacob, M. Mujumdar, and R. Krishnan (2011), Precipitation variability over the South Asian monsoon heat low and associated teleconnections, *Geophys. Res. Lett.*, *38*, L08702, doi:10.1029/2011GL046984.

1. Introduction

[2] The Asian summer monsoon system can broadly be divided into two subsystems, the Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM) system, which are to a greater extent independent of each other and, at the same time, interact with each other [*Kripalani and Singh*, 1993; *Wang and Fan*, 1999; *Wang et al.*, 2001; *Ding and Chan*, 2005]. On interannual time scales, the monsoon rainfall over India and northern China (southern Japan) are known to co-vary in phase (out of phase) indicating a common element of large-scale low-frequency variability [e.g., *Kripalani and Singh*, 1993; *Kripalani and Kulkarni*, 1997, 2001; *Krishnan and Sugi*, 2001]. While it is known that El Niño/Southern Oscillation (ENSO) is an important contributor to the interannual variations of monsoon rainfall over the two regions [e.g., *Walker*, 1924; *Webster and Yang*, 1992; *Wang et al.*, 2000; *Fasullo and Webster*, 2002; *Hu et al.*, 2005], a substantial portion of monsoonal variability, particularly over South Asia, also arises from the strong internal dynamics and convectively coupled processes of the monsoon system [e.g., *Palmer and Anderson*, 1994; *Sperber and Palmer*, 1996; *Sugi et al.*, 1997; *Goswami*, 1998; *Krishnan et al.*, 2009].

[3] Observations suggest that the interannual variability of the EASM rainfall is related to the west North Pacific summer monsoon heat source, as well as the convection over the ISM domain [*Wang et al.*, 2001]. Studies have reported two upper level barotropic anticyclonic anomalies during the excess ISM years, one located over the western central Asia and another over East Asia [e.g., *Krishnan and Sugi*, 2001; *Wang et al.*, 2001]. *Ding and Wang* [2005] found a circumglobal wave train in the northern hemispheric during boreal summer and pointed out that the CGT pattern can favor co-varying patterns of rainfall anomalies over South and East Asia. In fact the recent summer monsoon of 2010 is a good example to illustrate the out-of-phase rainfall and circulation variability between the two regions. Figure S1 of the auxiliary material[1] shows that the anomalous rainfall enhancement over Northwest-Central India and Pakistan is associated with convergence of winds from the Arabian Sea and Bay-of-Bengal; whereas a large-scale anticyclonic anomaly can be seen over the Northwest Pacific. In a previous study, *Saeed et al.* [2010] noted that the eastward propagation of mid-latitude wave train associated with the CGT modulates the surface pressure variations over the monsoon heat-low (HL) region (25°–35°N, 55°–75°E), and thereby favors enhanced southwesterly monsoonal flow and increased rainfall over northwestern India and Pakistan (NWIP). They found significant lead-lag correlations between the HL and the upper level circulation over western central Asia and also over East Asia. Despite the aforementioned studies, it is not yet adequately clear as to what extent the variability of rainfall/convection over the monsoon HL region can actually influence the large-scale circulation response and rainfall anomalies over East Asia. In the present study, we address the above question by conducting numerical simulation experiments using a high-resolution atmospheric GCM.

2. Methods

[4] In this paper, we have used the high resolution (T106L31) ECHAM5 climate model. A detailed description of ECHAM5 is given by *Roeckner et al.* [2003]. At high

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL046984.

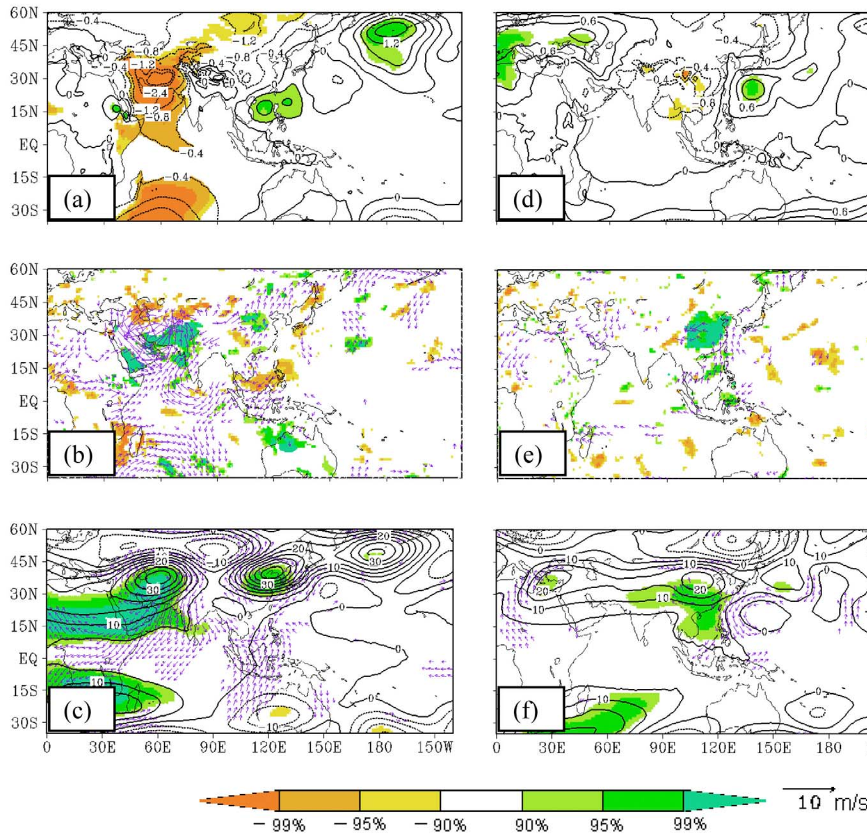

Figure 1. Mean difference of 21 summer seasons (June-September) from 1979-1999 between the intensified and shallow heat low experiment (IMSHL) (a) sea level pressure (hPa) (b) 850 hPa wind (vectors) and surface precipitation (shaded) (c) 200 hPa geopotential height (contours) and wind (vectors). The shaded areas in Figures 1a–1c indicate differences that are significant at 90% confidence level based on t-test for mean sea level pressure, surface precipitation and 200 hPa geopotential height respectively. The wind vectors associated to differences below 95% confidence level are omitted in Figures 1b and 1c. Negative contours in Figures 1a and 1c are shown by dashed line. (d, e) Similar to Figures 1a–1c except for EAIME experiment.

resolution, such as the one used here, ECHAM5 simulates reasonably well the mean climate [*Roeckner et al.*, 2006] and the HL-CGT relationship [*Saeed et al.*, 2010]. Similar to *Roeckner et al.* [2006], we have conducted a control AMIP-type run of the ECHAM5 at T106L31 resolution to verify the mean summer monsoon circulation pattern over Asia. It is found that the model simulates fairly well the salient features of the boreal summer mean monsoon circulation, e.g., the South Asian monsoon trough, the surface HL over northwest India and adjacent area, the southwest monsoon cross-equatorial flow, the Mascarene High, the upper-tropospheric Tropical Easterly Jet and the Tibetan anticyclone (Figure S2). Also the overall distribution of the summer monsoon rainfall over the Indian region is quite robust, as the model simulates reasonably well the precipitation maxima along the west coast and over Bay of Bengal (10°–20°N) and a small portion of rain shadowing area near western Ghatts (Figure S2).

[5] In addition to the control experiment, we have carried out two sensitivity simulations to examine the influence of convection variability over the monsoon HL region on the large-scale response. The strategy adopted for generating the convection variations over the monsoon HL region is by modifying the surface albedo. As pointed out by *Meehl* [1994], the lower land albedos are associated with warmer land temperatures, greater land-sea temperature contrast, and a stronger Asian summer monsoon. This approach has been adopted in our study to vary the convection over the monsoon HL region. The first experiment is the intensified heat low (IHL) run in which the convection over the surface HL is enhanced by reducing the surface albedo from 0.3 to 0.05 over the HL region (55°–75°E, 25°–35°N). The second experiment corresponds to the shallow heat low (SHL) run in which the convection over the HL is suppressed by increasing the surface albedo from 0.3 to 0.55 over the HL region. In each case the model is forced with observed sea ice and sea surface temperatures for the period from 01st January 1978 to 31st December 1999. The first year of each simulation is skipped and the analysis focuses on the remaining 21 summer seasons. Each summer season spans 122 days from 1st June to 31st September. Daily data are pre-processed with a 3-day running mean time filtering in order to eliminate synoptic variability. For simplicity the difference (IHL minus SHL) between the two experiments is referred to as IMSHL.

[6] In an accompanying set of experiments, we have also assessed the influence of convection variations over the East Asian monsoon region on the large-scale circulation response. For this purpose we carried out two additional simulations covering the same period as above, however, we

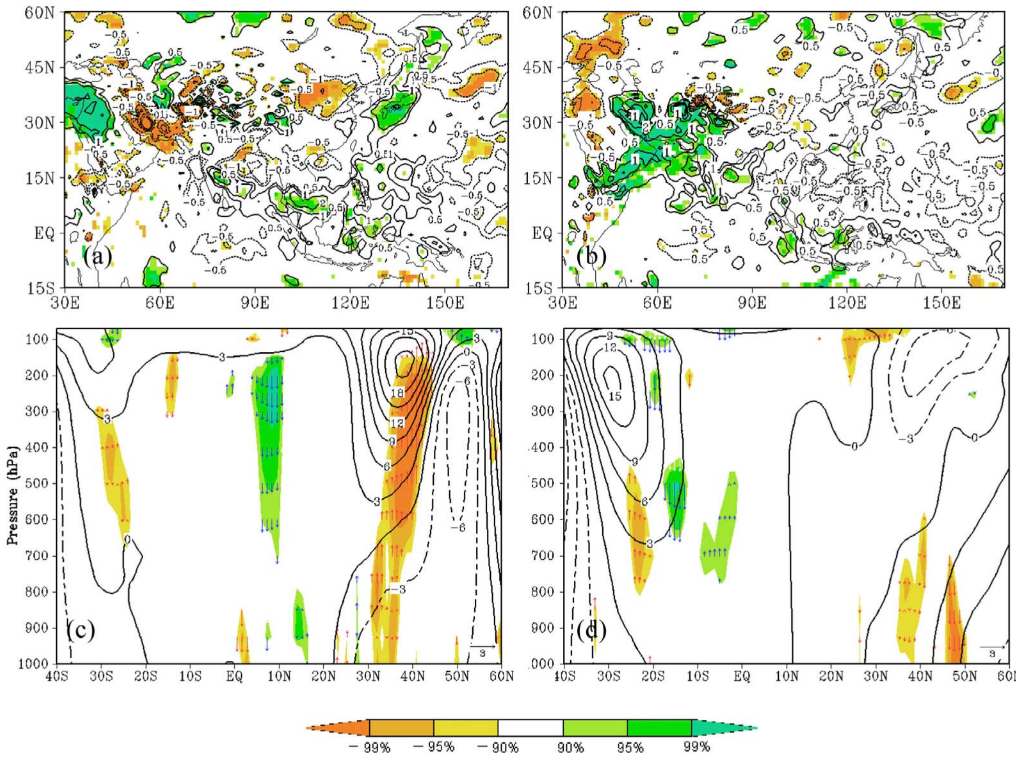

Figure 2. Mean differences of vertical velocity at 500 hPa (a) IHL minus Control experiment (b) SHL minus Control experiment. The difference in the height-latitude cross-section of vertical velocity (shaded) and geopotential height (contours) averaged between 100°–120°E (c) IHL minus Control experiment (d) SHL minus Control experiment. The difference is computed for 21 summer seasons (June-September) from 1979-1999 using monthly data. The shaded areas in Figures 2a–2d indicate differences that are significant at 90% confidence level for vertical velocity based on t-test. The vectors in Figures 2c and 2d indicate ascent (descent) if pointing upward (downward). The blue (red) vectors show significant increase (decrease) in ascent or descent. The wind vectors associated to differences below 90% confidence level are omitted in Figures 2c and 2d. The negative contours in Figures 2a–2d are shown by dashed lines.

first increased (decreased) the convection over the East Asia region (100°–120°E, 25°–35°N) by decreasing (increasing) the surface albedo. These two experiments are abbreviated as EAIL (EASL). The difference (EAIL minus EASL experiment) is referred as EAIMS. We have applied a t-test to assess the significance of the simulated response.

3. Results and Discussions

3.1. Analysis of IMSHL

[7] In the Asian monsoon region, the intensification of the HL is associated with significantly decreased pressure anomalies over the Arabian Sea and adjoining areas of Saudi Arabia and West Asia (Figure 1a). High-pressure anomalies over the South China Sea and the northwestern Pacific can also be noted in Figure 1a. The low level 850 hPa wind flow (Figure 1b) shows convergence of the flows from the Arabian Sea and the Bay of Bengal occurring over the NWIP and adjoining areas, with accompanying rainfall anomalies over the region. It is also interesting to note that the large-scale structure of the wind anomalies in Figure 1b shows anomalous divergence over the South China Sea. The upper-tropospheric wind anomalies in Figure 1c are nearly out-of-phase with the low-level circulation response. Furthermore, it can be noticed that the enhanced rainfall over the HL and adjacent areas is characterized by a wave like response in the upper levels similar to CGT (Figures 1b, 1c, 2a, and 2c). Studies have examined the influence of large-scale circulation anomalies on the precipitation variability over northern China [e.g., *Wang et al.*, 2001]. The strong convergence of the low level moist southerly flow favors enhanced precipitation and upper level divergence over northern China (Figures 1b and 1c). On the other hand, the suppressed rainfall over the South China Sea is associated with anomalous low level divergence over the region (Figure 1b). The map of vertical velocity anomalies at 500 hPa for the IHL experiment reveals anomalous ascent over the HL region and also over northern China (30°–45°N, 100°–120°E) as seen from Figures 2a–2c. However when rainfall over the HL region is suppressed, the large-scale teleconnection is absent over the East Asia monsoon region (Figures 2b and 2d). In other words, the large-scale circulation response to decrease of precipitation over the HL region is not simply a mirror image of the response to increased precipitation over the HL region. Furthermore, it must be pointed out that the rainfall over the HL region show larger variability in case of the IHL (standard deviation 1.53 mm day^{-1}) as compared to the SHL (standard deviation 0.79 mm day^{-1}) (Figures 3a and 3b). Thus the likelihood of the occurrence of heavy rainfall over NWIP increases in case of IHL.

[8] The ISM displays positive correlations with rainfall over northern China suggesting co-occurrence of floods and droughts over both regions [*Kripalani and Kulkarni*, 2001].

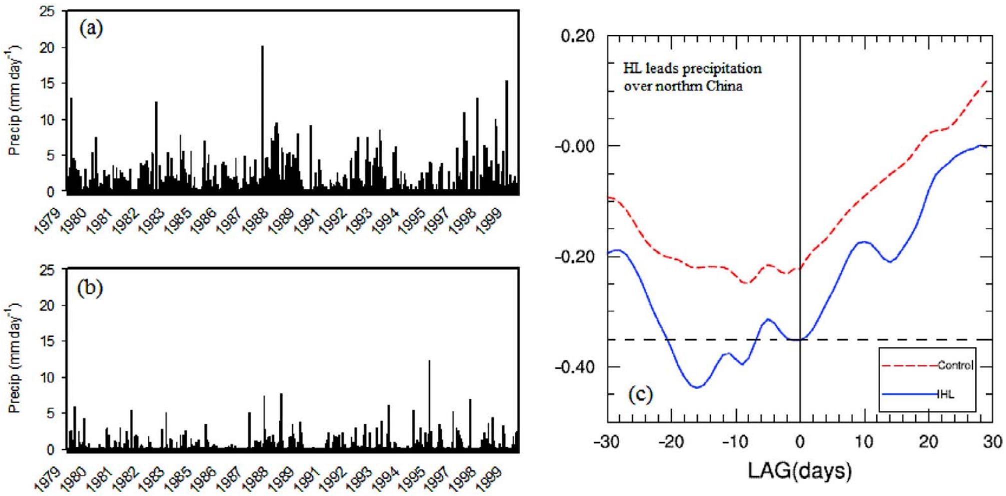

Figure 3. Area averaged daily rainfall over the HL region (a) IHL, (b) SHL. (c) The lead-lag correlations between the sea level pressure over HL region and rainfall over northern China (35°–42°N, 100°–120°E). The solid and dashed line in Figure 3c represents the correlations during the intense HL years and the Control experiment respectively. Out of 21 year 7 years are identified as IHL years. The horizontal dashed line in Figure 3c represents the 95% confidence level for correlations using the t-test.

To further examine this relationship, we also carried out a lead-lag correlation analysis between the sea level pressure over HL and precipitation over northern China (35°–42°N, 100°–120°E). For this purpose we first computed the intense HL years. The years when the sea level pressure anomalies over the HL region [*Saeed et al.*, 2010] are below 0.5 standard deviations are considered as intense HL years. Out of 21 years only 7 years are indentified as intense HL years. We found that the sea level pressure over the HL region leads precipitation over northern China by several days with maximum correlation occurring between 10–20 leading days (Figure 3c). Though statistically significant the correlations are small. It is realized that the East Asian monsoon variability is influenced by number of other factors like convection and circulation changes over the north of Philippines [*Nitta*, 1986, 1987], northwest Pacific heat source [e.g., *Wang et al.*, 2001], El Nino Southern Oscillation [e.g., *Huang and Wu*, 1989; *Zhang et al.*, 1999; *Wang et al.*, 2000], the tropical Indian Ocean sea surface temperature [e.g., *Li et al.*, 2008], the north Atlantic Oscillation [e.g., *Sung et al.*, 2006], etc. However, we tested the significance of the correlation value for HL leading the precipitation up to 20 days by evaluating a nonparametric estimate for the likelihood of a nonrandom occurrence of the result using a bootstrap method [e.g., *Zanchettin et al.*, 2008]. In this lead-lag range, the correlation values test as significant above the 95% confidence against a random occurrence, thereby suggesting a linkage of the detected signal to the true features of the process. Basically, the circulation response over the East Asian monsoon region can be interpreted as large-scale quasi-stationary waves induced by convection changes over the monsoon HL region. It is known that the summertime upper-tropospheric westerlies extending over West-Central Asia and the northern flanks of the Indo-Pakistan region can act as a waveguide and allow generation of stationary wave patterns [see *Ambrizzi et al.*, 1995; *Terao*, 1999; *Enomoto et al.*, 2003; *Ding and Wang*, 2005; *Krishnan et al.*, 2009]. *Terao* [1999] showed that eastward propagating waves along the westerly jets in the upper troposphere are more strongly trapped in the westerly jet than the westward propagating ones. Therefore, convectively generated wave motions over the heat-low region have the potential to extend downstream up to the Far East in the form of large-scale quasi-stationary circulation anomalies. It is seen from the present results that the HL and associated precipitation/convection variability can also modulate the EASM rainfall variability.

3.2. Analysis of EAIMS

[9] The EAIMS reveals (Figures 1d–1f) remarkable differences in lower and upper level circulation and pressure patterns as compared to those simulated in the IMSHL (Figures 1a–1c). In this case, the anomalous response shows an east-west sea level pressure dipole with low pressure anomalies over land and high over the northwestern Pacific Ocean (Figure 1d). The associated low level cyclonic (anticyclonic) circulation over land (ocean) favors enhanced moisture convergence and hence precipitation over the northern China (Figure 1e). In contrast to the IMSHL which shows suppressed rainfall over the South China Sea and adjacent areas (Figure 1b), the EAIMS reveals enhanced rainfall starting from South China Sea to northern China. Moreover, the decreased rainfall over the northwestern Pacific Ocean due to the anticyclonic circulation extends eastward in case of the EAIMS which can influence the downstream regions of North Pacific and the US region as noticed by several previous studies [e.g., *Lau and Weng*, 2002; *Lau et al.*, 2004]. Furthermore, the large scale circulation response seen in the case of IMSHL over the Asian monsoon region (Figure 1c) is absent in EAIMS experiment (Figure 1f), suggesting the importance of the rainfall/convection variations over the South Asian monsoon heat low on the downstream circulation response over East Asia.

4. Summary and Conclusions

[10] The present study examined the rainfall variability over the South Asian monsoon HL and its response to the

large scale circulation and related summer rainfall over East Asia. For this purpose we imposed modifications to the South Asian monsoon HL by using the climate model ECHAM5 and performed high resolution (T106L31) simulations to investigate the related feedbacks to the Asian monsoon climate. Results suggest that the rainfall/convection variability over South Asian monsoon HL region can influence the EASM rainfall variability through the tropical and extra-tropical components of large-scale teleconnections. The intensification of the HL favors enhanced convection and rainfall above HL region. The enhanced rainfall/convection above HL is further associated with a wave like response in the upper level similar to the CGT pattern extending well into the Asian monsoon region. At lower levels, the strong convergence above HL favors significantly enhanced cross equatorial flow across the India-Africa region and anomalous divergence above the South China Sea. The existence of this teleconnection is further supported by small but statistically significant lead-lag correlations between the heat low and precipitation over northern China. Conversely, a suppressed convection and rainfall above HL region do not display significant circulation anomalies above East Asia region.

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