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Changing Monsoon Extremes and Dynamics: Example in Pakistan

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1. Introduction

The Pakistan floods of 2010 constituted an extreme hydrologic event with substantial sociological consequences. At their height they submerged roughly 20% of Pakistan's land area, killing and injuring nearly 5,000 people directly, and displacing as many as 20 million. Though influenced by additional factors (*e.g.*, snowmelt and water management practices), the floods were closely tied to an unusually heavy rainfall event. The countrywide precipitation total during July–September 2010 was the highest since 1994 and the sixth highest in the last 50 years (PMD 2010). The weather event that led to flash floods in 2010 began with a series of local, intense rainstorms in July, followed immediately by monsoon rain throughout the first half of August. Synoptic analysis by Houze *et al.* (2011) pointed out that both the intensity and structure of the July rainstorms were abnormal for northern Pakistan. Due in part to myriad other extreme events in the summer of 2010, such as the Russian heat wave, questions have arisen as to whether the unusual 2010 Pakistan rainfall was simply a manifestation of climate variability or was connected in some measure with global climate change (Marshall 2010). The role of climate change in causing heavy monsoon rains needs to be addressed.

Here we summarize a recent paper by Wang *et al.* (2011) that examined the 2010 monsoon conditions, climatology, and trends. We further investigate the extent to which the trends are associated with internal variability vs. external forcing of the climate system. Additional results from a dynamical downscaling approach (*i.e.*, nesting regional climate models into global reanalyses) are also presented.

2. Data sources

We used the Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE; Xie *et al.* 2007), a gridded daily precipitation dataset derived from rain gauges with a 0.5° resolution for the period 1971–2007. The APHRODITE dataset allowed for an investigation of long-term daily precipitation over Pakistan, where stations with adequate records are sparse. Other data included the 3-hr Climate Prediction Center (CPC) Morphing technique precipitation (CMORPH; Joyce *et al.* 2004) for the analysis of the 2010 event, and the Tropical Rainfall Measuring Mission (TRMM)-based Lightning Imaging Sensor (LIS) 7-year climatology. For meteorological variables we used the ERA40 reanalyses (1971–2002) and the ERA-Interim reanalyses (1989–present; Uppala *et al.* 2005, 2008). These two reanalyses assimilated 2-meter air temperatures (T_{2m}). For data uniformity, we reduced the resolution of the ERA-Interim to be consistent with the ERA40 using bilinear interpolation. Finally, we performed downscaling simulations with the Weather Research and Forecasting (WRF) model, Advanced WRF (ARW) version 3.1, using the the National Centers for Environmental Prediction Reanalysis (NCEP2; Kanamitsu *et al.* 2002) as boundary conditions.

3. Results

a. Case analysis

The movement of the monsoon rainband and its association with the 2010 convective storms are displayed in Fig. 1a as the latitude-time diagram of CMORPH precipitation, and in Fig. 1b as the ERA-Interim's 850 mb relative vorticity and column-integrated precipitable water – all averaged between 70°E-75°E, which encompasses northern Pakistan. Three northward-moving monsoon troughs are readily visible in these meteorological fields. These features are typical of the 30–60 day mode of the Indian monsoon.

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However, only the second reached northern Pakistan (beyond 30°N), elevating moisture and producing near-continuous rainfall there during the first half of August. Arrival of the second monsoon trough also increased the convective available potential energy (CAPE; Fig. 1c contours) in northern Pakistan. In contrast, the three mesoscale convective systems (MCSs) responsible for the flash floods occurred during a drier and warmer period in July (arrow indicated), prior to the second monsoon trough's arrival; these features are discernible in the precipitable water and T_{2m} (Figs. 1b and 1c). Moisture surges accompany each MCS (Fig. 1b), apparently associated with passing synoptic disturbances as noted in Houze *et al.* (2011); these moisture surges are also evident in CAPE. Moreover, each of the MCSs occurred during the period when a series of midlatitude troughs intruded south, as is revealed in the 250 mb vorticity (not shown). Such a coupling between upper-level troughs and monsoon depressions exemplifies the tropical-midlatitude interaction that is known to take place over this region (*e.g.*, Chen *et al.* 2005). Such a feature, together with warm temperatures over sloping terrain and strong moisture gradients, suggests a thermodynamically unstable atmosphere prior to the monsoon trough's arrival in August.

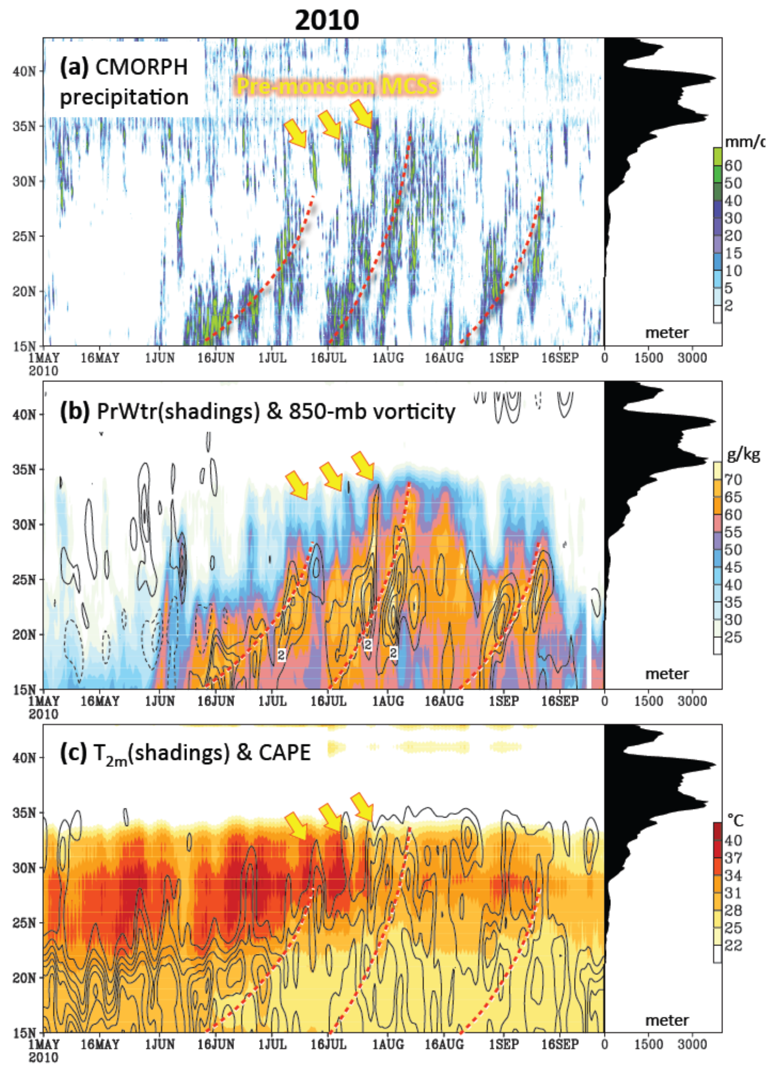

Fig. 1 Latitude-time diagrams for (a) CMORPH 3-hr precipitation, (b) precipitable water (shadings) and 850mb relative vorticity (contour interval 10^{-5} s^{-1} omitting zero and -10^{-5}), and (c) T_{2m} (shadings) and CAPE (contour interval 300 J Kg^{-1} beginning 300) averaged between 70°E and 75°E from May 1 to September 30, 2010. The three monsoon troughs are indicated by dashed lines. The three MCSs in July are indicated by yellow arrows. Mean elevation across the analysis area is shown to the right of each panel.

b. Climatology

The analysis in Fig. 1 suggests that the common description of the Pakistan monsoon as a single entity (*i.e.*, July as the monsoon onset and August as the mature monsoon) may not be adequate. Instead, these summer rains comprise two distinct phases of development: (i) a pre-monsoon trough phase with drier, warmer air and episodic strong convection; and (ii) a monsoon trough phase influenced by northward migrating monsoon troughs and associated humid, cooler air. Examination of climatological T_{2m}, dew point temperature (T_d), and total precipitation in northern Pakistan from 1971 to 2010 (Fig. 2) shows that the warmest T_{2m} occurs in June, with a rapid increase in T_d in response to the intrusion of moist air from the south. Then in July, T_{2m} begins to decrease; T_d reaches the seasonal maximum; and precipitation intensity peaks and is characterized by episodic features. In August, T_{2m} cools gradually while T_d peaks and then decreases in association with declining rainfall. These climatological features are in good agreement with the 2010 analysis in Fig. 1c, in which the July pre-monsoon trough phase comprises stronger instability and more intense convective systems. This can also be inferred from the increased lightning frequency accompanying the high values of both T_{2m} and T_d in Fig. 2—strong lightning activity being common prior to the monsoon onset (*e.g.*, Kodama *et al.* 2005). By contrast, the August monsoon trough phase is characterized by less episodic rainfall of decreasing intensity and declining lightning activity.

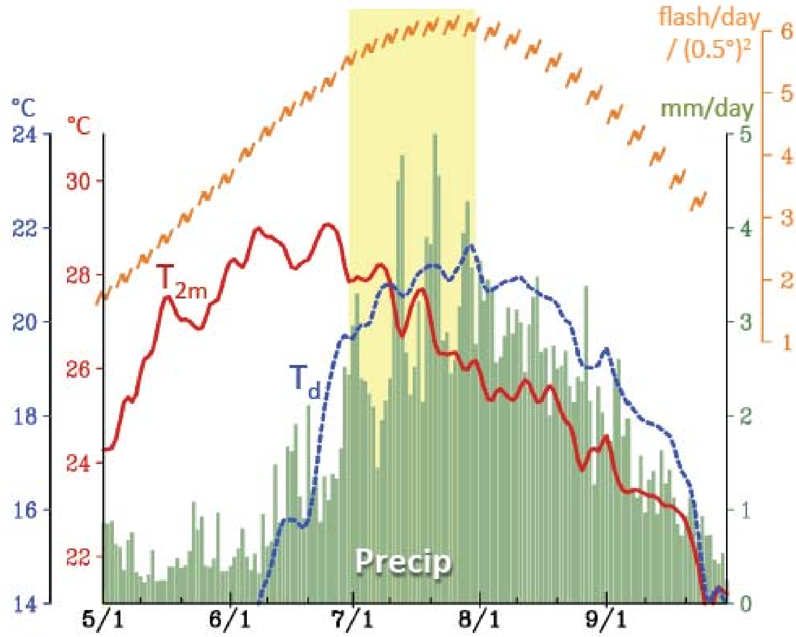

Fig. 2 Climatological means (1971-2009) of T_{2m} (red), Td (blue), precipitation (green bars), and lightning frequency (orange lightning symbols; plotted every 5 days) over northern Pakistan.

Such differences in the monsoon phases are also evident in the 10-day mean patterns of the 250 mb streamlines and precipitation in 2010 (Fig. 3). During July 10–20 (*i.e.*, the rainstorm episode), northern Pakistan is situated north of the monsoonal anticyclone, under a deepened synoptic trough to the immediate west. This feature echoes the upper-level "short waves" influence on rainfall (Khan 1993). Low-level circulations (850 mb) show that southwesterly flows prevail deeply inland over northern Pakistan, reflecting the moisture source of the MCSs. During August 1–11 (*i.e.*, the beginning of the monsoon trough episode), the monsoonal anticyclone matures and migrates north, completely covering northern Pakistan, while at 850 mb an enhanced monsoon trough migrates toward northern Pakistan, as outlined by the red dotted line in Fig. 3d.

c. Trends

The identification of two distinct phases in the northern Pakistan monsoon, attributable to separate environmental conditions, suggests separate analysis for each phase. Mean precipitation of both the July pre-monsoon trough phase (Fig. 4a) and the August monsoon trough phase (Fig. 4b), shows virtually no trend over the past 40 years (orange bars and line). This is consistent with the fact that the summer rainfall in 2010, albeit extreme, ranks only the sixth highest in observational history (PMD 2010). However, the convective nature of the pre-monsoon trough phase suggests the possibility that the unstable environment may be enhanced owing to post-1970 global warming—warming also evident in northern Pakistan (Figs. 4a and 4b). We analyzed the frequency of intense precipitation by computing the occurrences of grid-scale daily precipitation exceeding 5 mm (*i.e.*, one standard deviation of the monthly mean) and then averaging the occurrences in northern Pakistan. The frequency reveals a substantial upward trend in July (Fig. 4a; blue bars and line) but shows only a weak trend in August (Fig. 4b). A significance test of the trends is given in the caption, while trends excluding 2010 are overlaid as a cyan dashed line (apparently 2010 did not alter the trend). Moreover, the contrast between trends in the mean precipitation vs. the frequency of intense precipitation signifies an overall increase in rainfall intensity, which is linked to enhanced instability. This feature is particularly pronounced in the pre-monsoon trough phase of July.

d. Role of climate change

- *Diagnostics:* Since mean precipitation amounts in northern Pakistan reveal no trends, we focus the following analysis on the observed increase in convective activity. Atmospheric instability, especially during the pre-monsoon trough phase, is examined by the lapse rate of equivalent potential temperature (θ_e). The lapse rate, denoted as $d\theta_e/dp$, is shown in Fig. 5a with the climatological mean removed (shadings). A marked increase in $d\theta_e/dp$ is observed in the lower troposphere associated with a corresponding decrease in the upper troposphere. This suggests an overall increase in conditional instability, as well as potential instability for convective storms. In other words, additional moisture as seen in the increased T_d in Fig. 4a, combined with surface warming over sloping terrain, may have

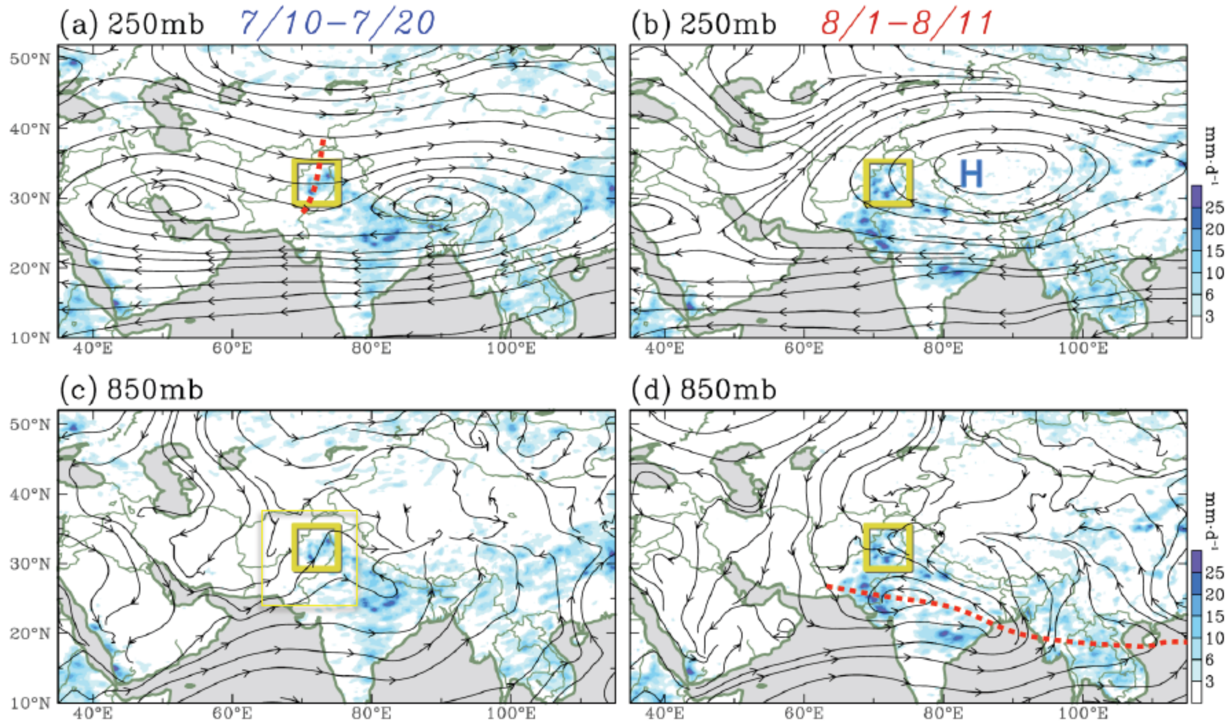

Fig. 3 Streamlines at 250 mb and the CMORPH precipitation (shadings) averaged in (a) 7/10-20 and (b) 8/1-11, 2010. The corresponding 850-mb streamlines are given in (c) and (d). Northern Pakistan is outlined by the yellow box. Red dashed lines in (a) and (d) indicate the synoptic-scale trough and the monsoon trough, respectively. The letter "H" in (b) indicates the monsoon anticyclone.

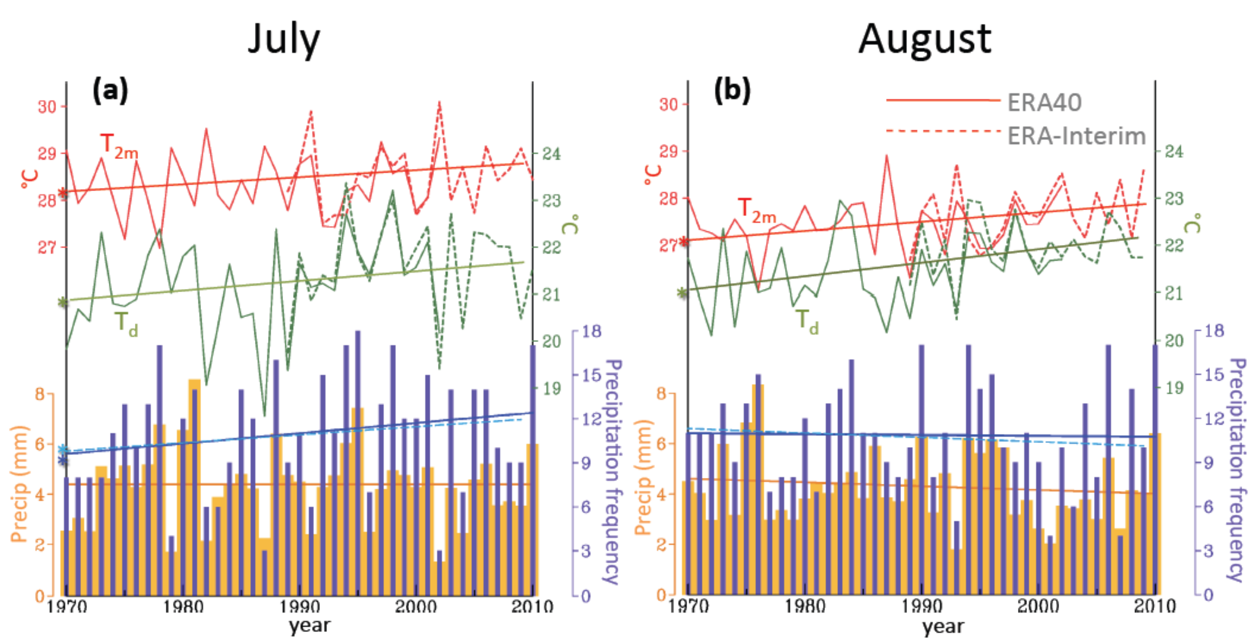

Fig. 4 Monthly mean T_{2m} (red line), T_d (green line), precipitation (orange bar), and frequency of intense precipitation (blue bar) over northern Pakistan in (a) July and (b) August, overlaid with linear trends. Dashed T_{2m} and T_d lines indicate data derived from ERAInterim (1989-2010). Trends that are significant at the 99% confidence interval (CI) are indicated by a star to the left, based on Student's *t*-test. Trends without a star are considered insignificant (*i.e.* < 99% CI). Trends without the inclusion of 2010 are shown as cyan dashed lines.

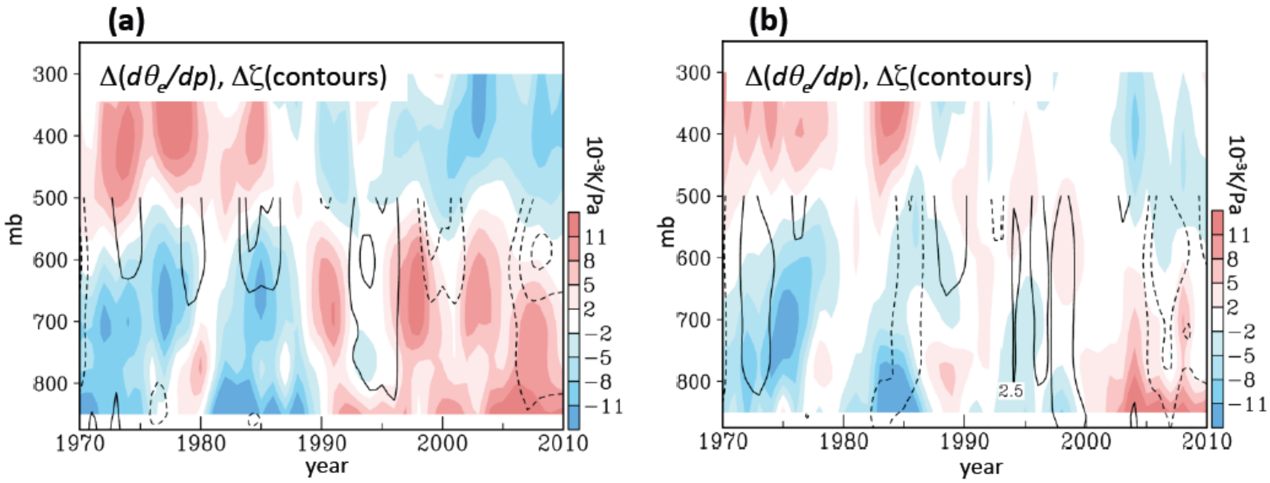

Fig. 5 Time-height cross-sections of the θ_e lapse rate (shadings) and relative vorticity (contour interval 10^{-5} s^{-1} omitting zero) averaged over northern Pakistan for (a) July and (b) August, with the long-term means removed, and divergence of water vapor flux (*i.e.* negative means convergence) during (c) July and (d) August. Linear trends in (c) and (d) are insignificant (blue broken lines).

enhanced conditional instability and, in turn, increased the chance for stronger convective precipitation events. Such a situation is also observed in the August monsoon trough phase (Fig. 5b), though the contrast of dθ_e /dp anomalies between the lower and upper troposphere is not as apparent as in July, except in the last decade. This recent enhancement of $d\theta_e /dp$ nonetheless coincides with the post-2000 increase in the frequency of intense precipitation (Fig. 5b, after 2000). To investigate changes in ambient circulation that may control variations in $d\theta_e /dp$, relative vorticity anomalies over northern Pakistan are overlaid on Fig. 5 as contours. There is no clear indication of increased or decreased low-level vorticity (*i.e.*, the monsoon trough); in fact, the negative vorticity anomalies prevailing in the last decade suggest a weakened monsoon trough, which would seem inconsistent with the increased frequency of intense precipitation.

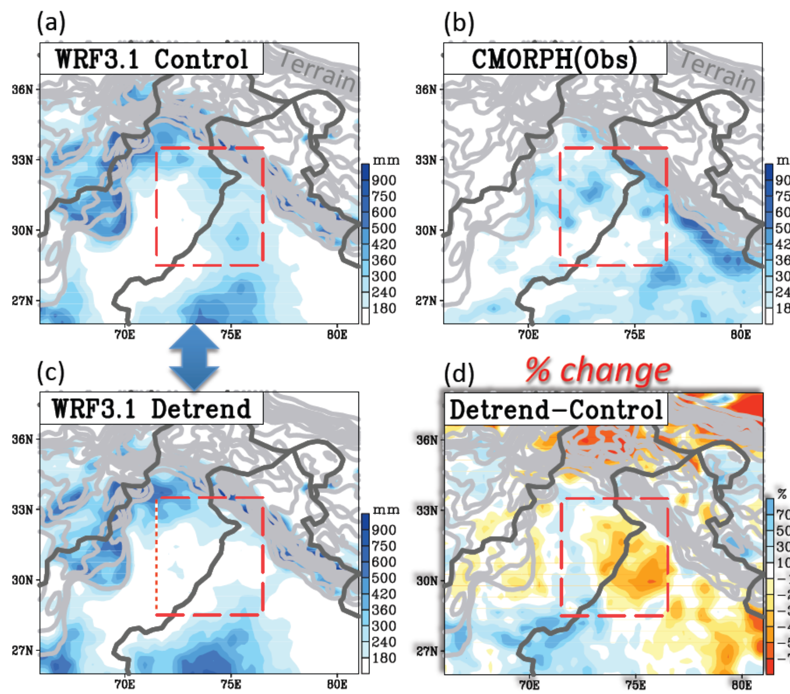

Fig. 6 WRF downscaling of July-August precipitation in 2010 from (a) control run, (c) "detrended run" (see text), and (d) their percentage change. Observed precipitation from CMORPH is shown in (b). Terrain is outlined by gray contours.

- *Modeling:* A WRF downscaling approach was adopted to quantify the impact of climate trends on the extreme nature of the 2010 precipitation event. We performed a control run using NCEP2 as boundary conditions during June–August at the 32 km resolution and compared it with another NCEP2 run that was "detrended" over the 1979–2010 period (on all input variables). The control simulation of July–August precipitation (Fig. 6a) reasonably depicts the observed features (Fig. 6b). The "detrended" simulation (Fig.

6c) shows an apparent reduction in precipitation over northern Pakistan and part of northern India. The reduction in rainfall over the rainstorm region is about 30%; all types of climate trends, including the post-1970 global warming signal, contribute to this reduction.

e. Dynamical implications

It is known that strong monsoons over India and Pakistan occur in association with enhanced upper-level anticyclones and an easterly jet (Webster 2006). To compare with the 2010 anomalies, we used the domain-averaged monthly precipitation over northern Pakistan (domain as in Fig. 6) to regress with the 200 mb geopotential height through 1974–2010. The regression pattern (Fig. 7a) depicts an anticyclone over and to the west of northern Pakistan, consistent with the literature. However, the July 2010 circulation anomalies reveal a marked cyclonic cell over northern Pakistan (Fig. 7b) rather than an anticyclone, as has been the case for strong monsoons. Noteworthy is the robust anticyclone over Eurasia that is linked to the Russian heat wave, embedded in the so-called circumglobal teleconnection (Branstator 2002). Such a discrepancy in the subtropical circulations is intriguing. As illustrated in Ding and Wang (2005), the upper-level anticyclone coupled with strong monsoons has a tropical "baroclinic" structure (*i.e.*, vertically reversed), whereas the rest of the Eurasian wave train features a barotropic structure (*i.e.*, vertically uniform). The 2010 cyclonic anomaly near northern Pakistan resembles the latter, which subsequently enhances southerly water vapor flux. This feature corresponds to the abnormal moisture supply and lifting mechanism found in the July rainstorms (Houze *et al.* 2011). The coupling of the monsoonal southerlies and the upper-level cyclonic flows also suggests a strong tropical-midlatitude interaction. Such interaction can further enhance conditional instability

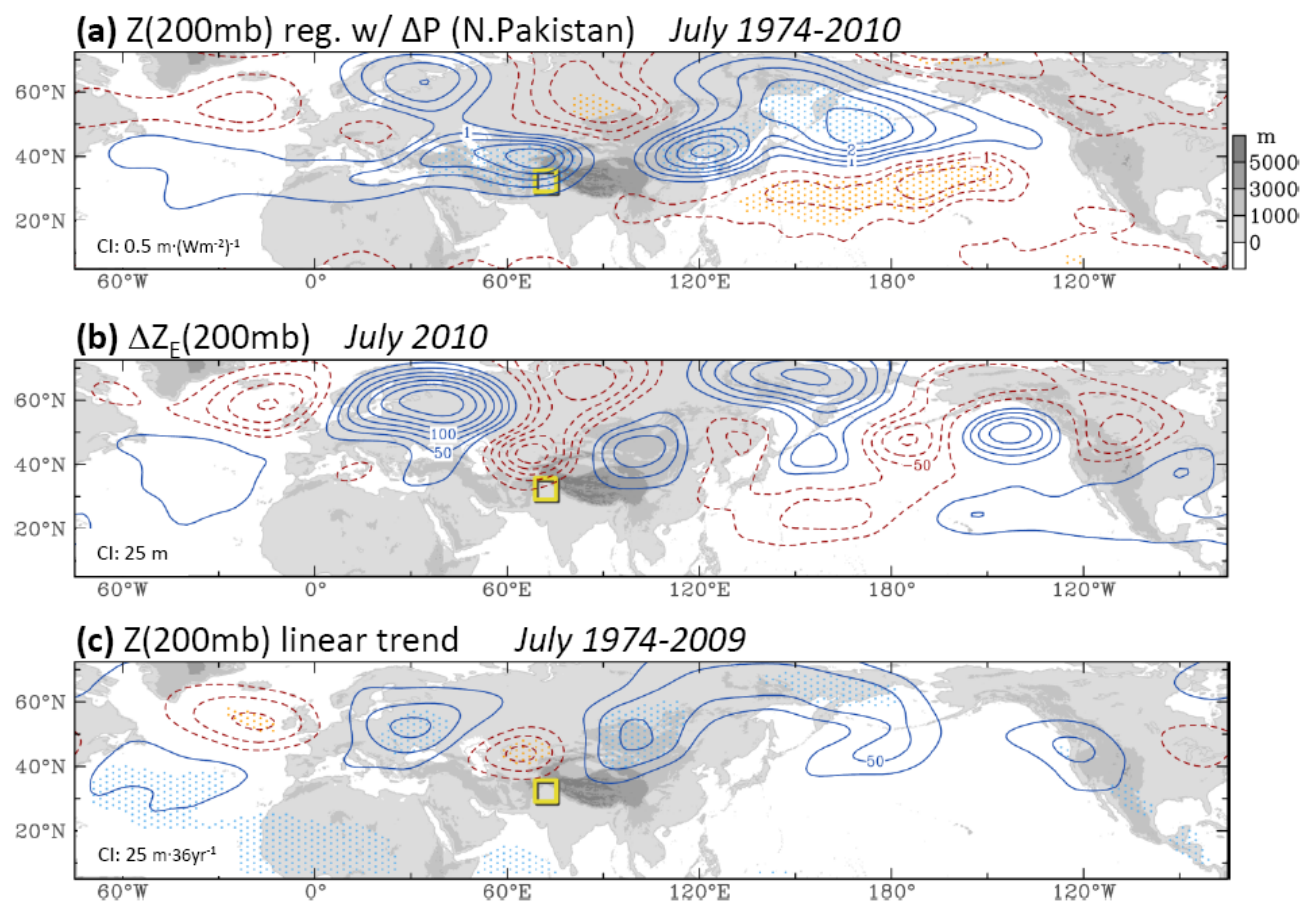

Fig. 7 (a) 200 mb geopotential height regressed upon ΔP averaged in northern Pakistan (yellow box) for July of 1974-2010, (b) departure of the July 2010 geopotential height from the climatology with the zonal mean removed, and (c) linear trends of the July geopotential height during 1974-2009. Dotted areas in (a) and (c) outline significant regions with the 99% confidence interval. Background shadings indicate the topography.

owing to the combination of high temperature and increased moisture (*cf.* Fig. 1). Regardless, any empirical model similar to Fig. 7a would suggest the cyclonic anomaly in 2010 be associated with a weak monsoon over Pakistan, rather than a strong one. This is alarming because such a departure from the empirical model would have led to false predictions of the monsoon.

Is the 2010 circulation pattern sporadic, or could it be systematic? Figure 7c shows the linear trends of geopotential height over the 1974–2009 period; the year 2010 was removed in order to conduct an independent assessment of the trends. The result reveals a zonally oriented wave train that is in-phase with the 2010 circulation pattern across the North Atlantic, Eurasia, and East Asia. Such long-term circulation changes may be associated with the Eurasian warming of recent decades, a phenomenon thought to enhance a land-ocean thermal gradient conducive to a strong monsoon in India (Kumar *et al.* 1999). However, the cause of the transcontinental wave train and its changing relation with the Indian monsoon is complex and requires further analysis.

4. Discussion and conclusion

We summarized the paper of Wang et al. (2011), which examined the 2010 summer precipitation in Pakistan and its link with climate change, and introduced a new dynamical downscaling analysis. We suggest that summer precipitation in northern Pakistan comprises two distinct phases: a pre-monsoon trough phase (July) with more-episodic and intense rainfall, occurring without the monsoon trough; and a monsoon trough phase (August) with large but less-episodic rainfall, driven by northward advancement of the monsoon trough coupled with the 30–60 day mode. It is demonstrated that separating the two monsoonal phases aids in the detection and attribution of climate change signals. Long-term trends linked to the 2010 summer rainfall saw an intensification of the pre-monsoon trough phase only. Diagnostic analyses support such intensification as part of a long-term (and ongoing) process—an observation consistent with expectations from a warming and moistening lower troposphere. Conversely, evidence does not support long-term intensification of the August monsoon trough phase in northern Pakistan, nor any trend in the northward extension of the monsoon rainband (other than that accounted for via internal climate variability such as the La Niña).

Large-scale circulation analysis suggests that the typical linkage between increased monsoon rains in northern Pakistan and enhanced anticyclones in the upper troposphere has changed, such that cyclonic anomalies combined with enhanced conditional instability (*i.e.*, due to a warming surface and increasing moisture supply) could also trigger intense precipitation—a process substantiated through the unambiguous increase in convective activity. Various global reanalyses agree that the circulation pattern in July 2010, while abnormal, is not sporadic. Instead, it is part of a long-term trend of the larger-scale circulation that defies the typical monsoon dynamics expected in northern Pakistan (*i.e.*, strong monsoons associated with upper-level anticyclones). At this point it is reasonable to conclude that the increased convective activity in northern Pakistan is not only a result of unusual circulation anomalies (*i.e.*, internal variability), but rather is a combined process of circulation changes acting on local destabilization due to warming and moistening of the lower troposphere (*i.e.*, internal + external variabilities). This process may, at least partially, explain the observation by Houze *et al.* (2011) that "the rainstorms responsible for the floods were of a type that does not normally occur in this region."

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