# Pacific Ocean sea-surface temperature variability and predictability of rainfall in the early and late parts of the Indian summer monsoon season

**Balaji Rajagopalan · Peter Molnar**

**Abstract** For central India and its west coast, rainfall in the early (15 May–20 June) and late (15 September–20 October) monsoon season correlates with Pacific Ocean sea-surface temperature (SST) anomalies in the preceding month (April and August, respectively) sufficiently well, that those SST anomalies can be used to predict such rainfall. The patterns of SST anomalies that correlate best include the equatorial region near the dateline, and for the early monsoon season (especially since ∼1980), a band of opposite correlation stretching from near the equator at 120°E to ∼25°N at the dateline. Such correlations for both early and late monsoon rainfall and for both regions approach, if not exceed, 0.5. Although correlations between All India Summer Monsoon Rainfall and typical indices for the El Niño-Southern Oscillation (ENSO) commonly are stronger for the period before than since 1980, these correlations with early and late monsoon seasons suggest that ENSO continues to affect the monsoon in these seasons. We exploit these patterns to assess predictability, and we find that SSTs averages in specified regions of the Pacific Ocean in April (August) offer predictors that can forecast rainfall amounts in the early (late) monsoon season period with a ∼25% improvement in skill relative to climatology. The same predictors offer somewhat less skill (∼20% better than climatology) for predicting the number of days in these periods with rainfall greater than 2.5 mm. These results demonstrate that although the correlation of ENSO indices with All India Rainfall has decreased during the past few decades, the connections with ENSO in the early and late parts have not declined; that for the early monsoon season, in fact, has grown stronger in recent decades.

**Keywords** Indian summer monsoon · Onset and withdrawal · Tropical Pacific SST-monsoon teleconnections

# 1 Introduction

Despite more than a century of study, predicting South Asian monsoon rainfall over the Indian subcontinent has progressed slowly even as modeling capability has grown (e.g., Goswami 1998; Kang et al. 2002; Sperber et al. 2001; Webster et al. 1998). In simple terms, the amount of rainfall seems to depend not only on local conditions over the Indian subcontinent and surrounding regions, but also on global conditions that affect large-scale circulation (e.g. Charney and Shukla 1981; Palmer et al. 1992; Webster et al. 1998). Not independent of this view, monsoon rainfall amount can be seen as depending on two of its aspects, its average intensity and the duration of the monsoon season (e.g. Fasullo and Webster 2003; Goswami and Xavier 2005; Joseph et al. 1994). Because of the clear dependence of monsoon season length on equatorial Pacific sea-surface temperatures (SST), we subdivide the question of predicting monsoon rainfall into a couple of questions that focus

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only on the early and late parts of the monsoon, which are most likely to be affected by equatorial Pacific SSTs: (1) can we predict rainfall amounts in the early and late parts of the monsoon?, and (2) For which parts of India are such predictions most reliable?

We pursue this first by addressing dates of onsets and withdrawals of the monsoon as the response to perturbations to global circulation associated with El Niño-Southern Oscillation (ENSO) variability, which is known to correlate with amounts of South Asian monsoon rainfall (e.g. Webster et al. 1998). We build on the observation that ENSO affects the duration of the South Asian monsoon (e.g. Fasullo and Webster 2003; Goswami and Xavier 2005; Joseph et al. 1994). We then exploit the gridded daily rainfall dataset of Rajeevan et al. (2006) to examine how rainfall amounts in different regions correlate both with onset and withdrawal dates and with ENSO indices. Using monthly observations (Kaplan et al. 1998), we identify regions that seem most sensitive to equatorial Pacific SSTs, and the locations within the Pacific Ocean where sensitivity is greatest. Finally, we assess the predictability of rainfall in different regions using SSTs in the Pacific Ocean.

We are motivated by the idea that predictions of onset and withdrawal dates and of rainfall amounts in the early and late parts of the monsoon season will help farmers and planners. Decisions that concern when to sow seeds, whether or not to irrigate, and when to harvest should benefit from such predictions.

## 2 Onset and withdrawal dates and their relationships to equatorial Pacific SSTs

Dates of onset and withdrawal for the South Asian, or Indian, monsoon differ depending on what aspect of the monsoon is used. Some consider rainfall over the Indian subcontinent, focusing on when rainfall on the west coast of India becomes intense and sustained (e.g. Ananthakrishnan and Soman 1989; Joseph et al. 2006; Pai and Nair 2009; Soman and Krishna Kumar 1993); some consider the abrupt strengthening of the Somali Jet (e.g. Fieux and Stommel 1977; Halpern and Woiceshyn 1999; Raju et al. 2005; Taniguchi and Koike 2006) including its impact on moisture transport to India (Fasullo and Webster 2003); and many address large-scale circulation associated with changes in meridional temperature gradients aloft or related large-scale circulation (e.g. Goswami and Xavier 2005; He et al. 1987, 2003; Li and Yanai 1996; Prasad and Hayashi 2005; Xavier et al. 2007; Yanai et al. 1992). Among the definitions based on these different criteria, all correlation coefficients, $r$, between various definitions of onset dates are $>0.5$, and for roughly half, $r > 0.7$ (e.g., Fig. 1a; Table 1). Fewer studies give withdrawal dates, but among those given by Fasullo and Webster (2003), Goswami and Xavier (2005), Prasad and Hayashi (2005), and Syroka and Toumi (2004), only those of Fasullo and Webster (2003) correlate with others with $r < 0.5$, and most other correlations exceed 0.6 (Table 2). Moreover, most such definitions of onset or withdrawal dates

**Fig. 1** Scatter plots of **a** GX05 (Goswami and Xavier 2005) onset dates versus IMD onset dates given by the India Meteorological Department (IMD) (Joseph et al. 2006), with the 1:1 line—the dates are Julian days, **b** GX05 onset dates versus All India Summer Monsoon Rainfall (AISMR) (mm) with the linear regression line (Parthasarathy et al. 1994), **c** Same as **b** but with GX05 withdrawal date and, **d** same as **b** but for GX05 season length. The corresponding correlation coefficient values are shown at the top in each figure
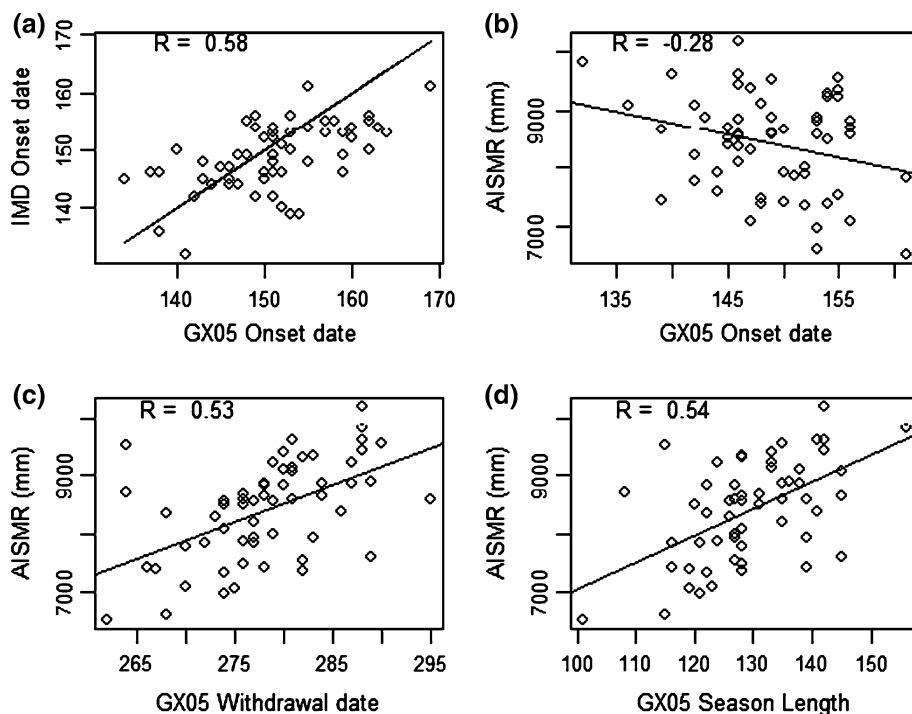
**Table 1** Matrix of correlations between pairs of onset dates of the South Asian monsoon in the upper right and significance of correlations in the lower left

|  | IMD | AS | Joseph | Pai | Prasad | Fasullo | Taniguchi | Goswami | Wang | Zhang |
|---|---|---|---|---|---|---|---|---|---|---|
| IMD | * | 0.86029 | 0.80995 | 0.87964 | 0.78007 | 0.58717 | 0.62519 | 0.63448 | −0.07507 | 0.08301 |
| AS | <0.001 | * | 0.84540 | 0.98547 | 0.86703 | 0.65901 | 0.71785 | 0.57236 | −0.13194 | −0.00840 |
| Joseph | <0.001 | <0.001 | * | 0.91422 | 0.78252 | 0.61710 | 0.69379 | 0.52908 | −0.11978 | 0.21864 |
| Pai | <0.001 | <0.001 | <0.001 | * | 0.81437 | 0.56165 | 0.68981 | 0.53243 | −0.15958 | 0.24760 |
| Prasad | <0.001 | <0.001 | <0.001 | <0.001 | * | 0.64457 | 0.80878 | 0.73433 | +0.06278 | 0.24657 |
| Fasullo | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | * | 0.64827 | 0.53991 | −0.08512 | 0.00133 |
| Taniguchi | <0.001 | 0.009 | <0.001 | <0.001 | <0.001 | <0.001 | * | 0.61497 | +0.11214 | 0.10593 |
| Goswami | <0.001 | <0.001 | 0.002 | 0.002 | <0.001 | <0.001 | 0.001 | * | −0.06546 | 0.39287 |
| Wang | 0.593 | 0.399 | 0.528 | 0.400 | 0.698 | 0.545 | 0.619 | 0.648 | * | 0.09192 |
| Zhang | 0.583 | 0.959 | 0.283 | 0.223 | 0.130 | 0.993 | 0.676 | 0.007 | 0.544 | * |

*IMD* Indian meteorological division, see Joseph et al. (2006)

*AS* Ananthakrishnan and Soman 1989

Joseph et al. (2006)

Pai and Nair (2009)

Prasad and Hayashi (2005)

Fasullo and Webster (2003)

Taniguchi and Koike (2006)

Goswami and Xavier (2005)

Wang et al. (2004)

Zhang et al. (2002)

**Table 2** Matrix of correlations between pairs of withdrawal dates of the South Asian monsoon in the upper right and significance of correlations in the lower left

|  | Prasad | Fasullo | Goswami | Syroka |
|---|---|---|---|---|
| Prasad | * | 0.0753 | 0.6501 | 0.7197 |
| Fasullo | 0.6315 | * | 0.3046 | 0.1134 |
| Goswami | <0.0001 | 0.0298 | * | 0.5411 |
| Syroka | <0.0001 | 0.4689 | 0.0002 | * |

Prasad and Hayashi (2005), Fasullo and Webster (2003) Goswami and Xavier (2005) Syroka and Toumi (2004)

(e.g. Ananthakrishnan and Soman 1989; Fasullo and Webster 2003; Goswami and Xavier 2005; Prasad and Hayashi 2005; Syroka and Toumi 2004; Xavier et al. 2007) show that early onsets and late withdrawals tend to be associated with more monsoon rainfall, as measured by the All India Summer Monsoon Rainfall index (AISMR), the June-to-September All India Rainfall (AIR) (Parthasarathy et al. 1994). Thus, despite their differences, all definitions share some commonality.

We exploit Goswami and Xavier's (2005), hereafter GX05, definition of onset and withdrawal, first because, like others with different criteria for defining onset and withdrawal dates (e.g. Fasullo and Webster 2003; Joseph et al. 2006; Prasad and Hayashi 2005; Syroka and Toumi 2004; Xavier et al. 2007), their dates show a clear dependence on ENSO, and second, because they give onset and withdrawal dates spanning a relatively long time interval, now updated to 1948–2009 (B. N. Goswami, personal communication 2010). To define onset and withdrawal dates, they calculated average temperatures in the upper troposphere, between 700 and 200 hPa, in two latitude bands between 50° and 90°E over eastern Asia: 10°–35°N and 15°S–10°N. They examined both NCEP (Kalnay et al. 1996) and EAR (Uppala et al. 2005) reanalyses, and concluded that the former seemed the more reliable for their purposes. They defined monsoon onset (withdrawal) dates as those when the northern region becomes the warmer (cooler).

GX05 showed that the correlation of monsoon duration, between their onset and withdrawal dates, with the Niño3.4 index (average SST between 5°N and 5°S and between 170°W and 120°W) remained $<-0.6$ throughout the period from 1960 to 1991. This sustained negative correlation differs from the correlation of AISMR with the Niño3.4 index, which ranged from $-0.5$ to $-0.6$ before $\sim$1980, but then became insignificantly different from zero at 95% confidence since $\sim$1980 (Krishna Kumar et al. 1999). In fact, the correlation of GX05's onset and withdrawal dates with summer monsoon rainfall over India (AISMR) are also significant (Fig. 1b, c, d). More important, as we show below, those correlations are yet better when the early and late parts of monsoon rainfall on India are treated

**Fig. 2** Scatter plots of **a** GX05 onset dates and all India early rainfall (AIER) in the period 20 May to 15 June, and **b** GX05 withdrawal dates and all India late rainfall (AILR) in the period 20 September to 15 October, each also with linear regression lines. Correlation coefficients are $r = -0.58$ (**a**) and $r = 0.65$ (**b**)
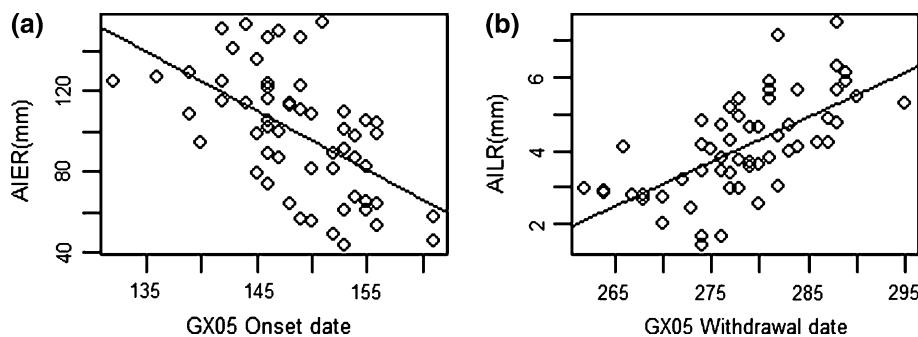
separately (Fig. 2) from the total rainfall during the entire monsoon season (AISMR).

We extended the work of GX05 to ask how well the patterns that they recognized can be used to predict Indian monsoon onset and withdrawal dates, as defined by their criteria. In a first pass, to characterize the ENSO signature, we exploited not only the Niño3 index (average SST between 5°N and 5°S and between 150°W and 90°W), which most have used, and the Niño3.4 index, but also the Niño4 index (the average SST between 5°N and 5°S and between 160°E and 150°W). As should be clear below, the Niño4 index seems to correlate slightly better than the others, especially for the past 30 years.

Fasullo and Webster (2003) and GX05 showed that the monsoon season length correlates with summer (June–September) SSTs in the tropical eastern and central Pacific, with Fasullo and Webster (2003) using the Niño3 index and GX05 the Niño3.4 index. A connection between ENSO and monsoon rainfall amount is known well via the subsidence limb of the Walker circulation over the Indian Ocean (e.g. Krishna Kumar et al. 1999, 2006; Palmer et al. 1992). Indeed, SSTs (Kaplan et al. 1998; http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.EXTENDED/.v2/.ssta/) across much of the equatorial Pacific correlate negatively with monsoon duration (Fig. 3a); low temperatures in the Pacific correlate with long monsoon seasons. As Syroka and Toumi (2004) found using the Niño3 index and their determinations of withdrawal dates, GX05's withdrawal dates correlate negatively with summer eastern Pacific SSTs and best with September SSTs, the month in which monsoons commonly withdraw; later withdrawals (larger Julian dates) correspond to both a cooler tropical central Pacific and a warmer maritime continent and subtropical Western Pacific (Fig. 3c). The same logic applies to the correlation of onset dates with May SSTs, except that signs of correlations are reversed to account for an earlier monsoon (smaller Julian date) when the tropical central Pacific is relatively cool (Fig. 3b). Note that magnitudes of these correlations are greatest for SSTs near the dateline (Fig. 3), which suggests better correlations with the Niño4 index than either the Niño3.4 or Niño3 indices. The

prominent correlations in the central Pacific Ocean ($r > 0.4$ for onset and $r < -0.6$ for withdrawal dates in Fig. 3) are reminiscent of the ENSO correlation of less monsoon rainfall with a warm central Pacific. Thus, these patterns support the ENSO connection not only with monsoon rainfall amount, but also with onset and withdrawal dates that others have inferred (e.g. Fasullo and Webster 2003; Joseph et al. 2006; Prasad and Hayashi 2005; Syroka and Toumi 2004; Xavier et al. 2007).

## 3 Predictability of early and late monsoon season rainfall

The analysis above shows that the onset and withdrawal dates of the Indian Monsoon can be predicted with some skill, but obviously farmers and resource planners are unlikely to be aware of, let alone pay much attention to, predictions that characterize phenomena in the upper atmosphere, as GX05's onset and withdrawal dates do. To be useful, such predictions must also bear on rainfall.

Onset dates of monsoons are commonly at the end of May or the beginning of June, and withdrawal dates are near the end of September and occasionally in early October. Rainfall amounts, averaged over all of India (AIR) (e.g. Parthasarathy et al. 1994), in the early monsoon period of 20 May to 15 June and in the late monsoon period of 20 September to 15 October correlate with onset ($r = -0.56$) and withdrawal ($r = 0.65$) dates, respectively (Fig. 2). Thus, the correlations of onset and withdrawal dates with equatorial Pacific SSTs offers the possibility of predicting rainfall amounts in the early and late parts of the monsoon, which should be useful to resource planners and farmers, despite their inability, at least as measured by the Niño3 index, to predict All India Summer Monsoon Rainfall amount skillfully (DelSole and Shukla 2002).

It is widely known (e.g. Krishnamurthy and Shukla 2000; Pant and RupaKumar 1997) that the monsoon begins and withdraws at different times in different places, and that strong monsoon rainfall in some regions correlates poorly with that in others (Krishnamurthy and Shukla

**Fig. 3** Correlation maps **a** of GX05 season length with June–September SST, **b** GX05 onset dates with May SST, and **c** GX05 withdrawal dates with September SST
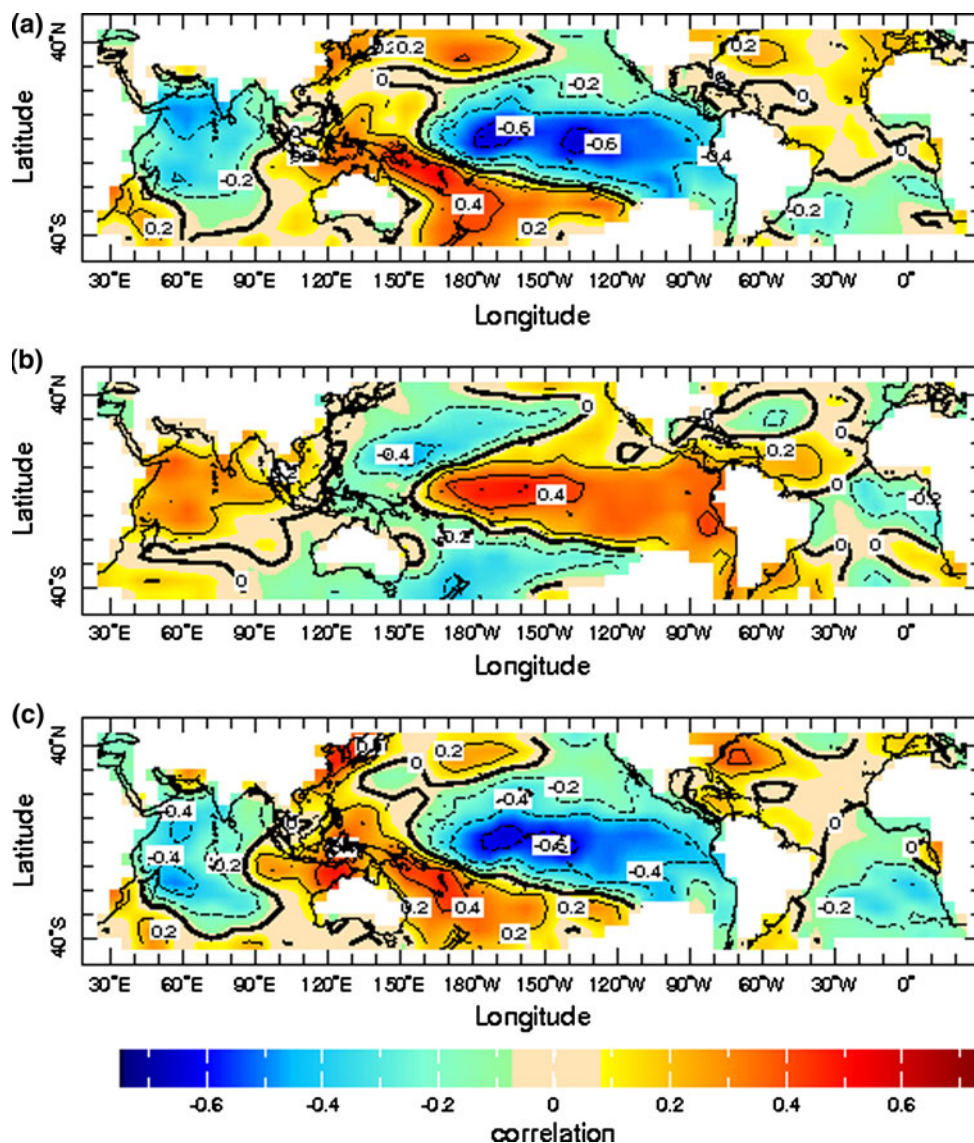
2007) (Fig. 4). Thus, a skillful prediction of onset or withdrawal dates need not be useful for all of India. With that fact in mind, we examined the spatial variability of monsoon rainfall using the gridded daily rainfall compilation of Rajeevan et al. (2006) and its updates. Rainfall in both the early and late parts of the monsoon is concentrated along the coasts, especially the west coast, and in the northeastern part of the country (Fig. 4). The arid northwestern part of the country receives the least rainfall. As is well known (e.g. Ihara et al. 2008; Krishnamurthy and Shukla 2007; Pant and RupaKumar 1997), rainfall over northeastern India correlates poorly with that over most of the rest of the country. Rainfall across much of central India and along the west coast of India is greater in the period 20 May to 15 June when the onset date is early (Fig. 5a) and in the period 20 September to 15 October when the withdrawal date is late (Fig. 5b). As might be

expected too, the correlation is poor, even opposite in sign over part of northeast India (Fig. 5a). A portion of southern India shows similarly opposite correlations to those over the west coast and much of central India (Fig. 5).

Rainfall amount is not the only quantity of socio-economic importance, for light rains do not necessarily remain as groundwater; they can evaporate rapidly. This is especially important during the early season as spells of heavy rain are crucial for the sowing of successful crops. Thus, we also examined the number of days with rainfall in excess of 2.5 mm for the early monsoon period. Over much of India, that number of days in the period 20 May to 15 June also correlates with GX05's onset dates (Fig. 5c). A similar plot (not shown) applies to the number of days with rainfall greater than 5 mm.

The somewhat better correlation with onset than with withdrawal dates (Fig. 5) in regions of heavier rainfall
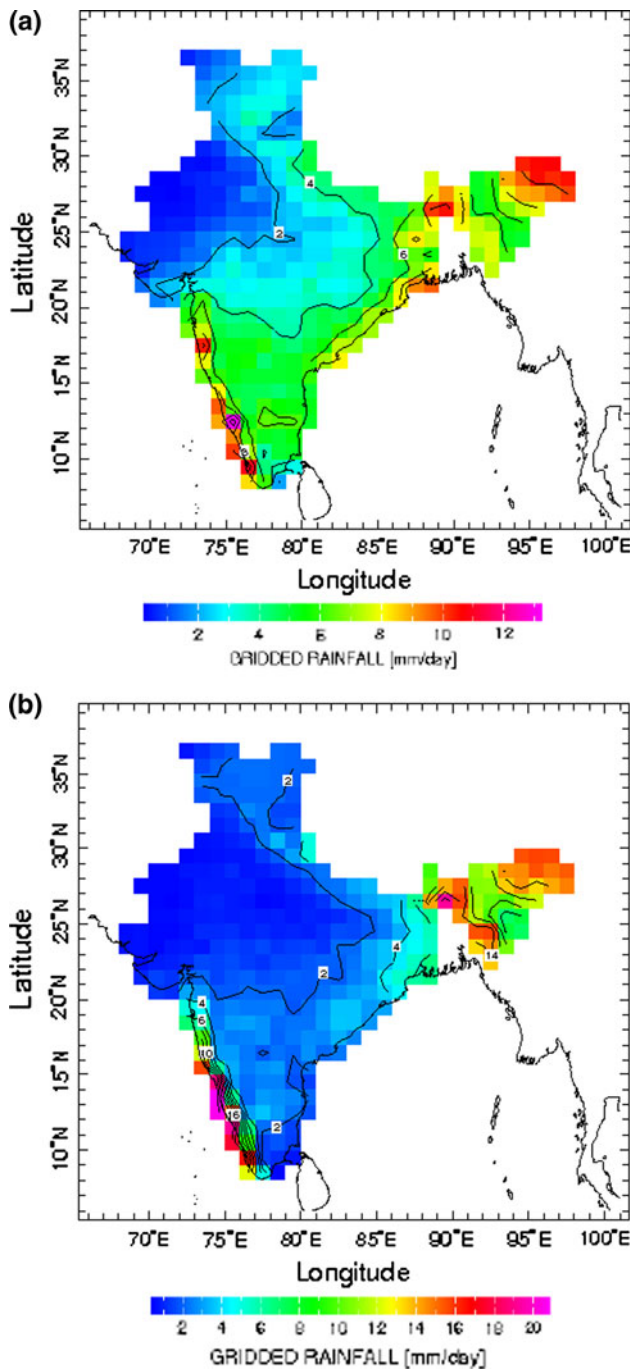
Fig. 4 Climatology of gridded rainfall (Rajeevan et al. 2006) for the periods **a** 20 May to 15 June, and **b** 20 September to 15 October

(west coast and east central India near the east coast: Fig. 4) may derive from surface conditions over India, which depend on how wet and cool the surface is and when rain fell last (e.g. Saha et al. 2011). Differences in resulting surface temperatures seem likely to be greater in the pre-monsoon period than later, when the monsoon is underway. Hence these surface conditions may affect early monsoon rainfall more than late monsoon rainfall (e.g. Saha et al.

2011). The surface tends to be dry and becomes especially hot just before the onset of monsoon rains, but a small amount of pre-monsoon rainfall might delay the onset of heavy rainfall associated with the onset of the monsoon.

The correlations shown in Figs. 4 and 5 suggest that socio-economically useful predictions of early and late season rainfall could be made using GX05's onset and withdrawal dates. Since we are most interested in pre-dicting rainfall, however, not onset or withdrawal dates, we exploit their relationships with Pacific SSTs directly, by using the latter as predictors. For both the early (May 20–June 15) and late (September 20–October 15) periods of the monsoon, we examined two regions: central India (15°N–30°N, 70°E–85°E) and the west coast (8°N–20°N, 65°E–76°E) (Fig. 4), where both rainfall amounts and numbers of days of heavy rainfall correlate best with GX05's onset dates (Fig. 5). Further, these regions are important from the standpoint of agriculture and water resources.

A map of correlations of April SSTs with early season rainfall in central India (15°N–30°N, 70°E–85°E: Fig. 4) shows a pattern (Fig. 6a) similar to those both (1) of canonical El Niño SST anomalies and (2) of correlations of SSTs with GX05's onset dates (Fig. 3). Negative correla-tions reaching $r = -0.2$ over the equatorial Pacific between the dateline and ∼150°W imply that relatively high (low) SSTs in these regions in April correspond to atypically low (high) rainfall over central India in the early monsoon period from 20 May to 15 June; vice versa rainfall is positively correlated, with $r > 0.4$, with SSTs over the western Pacific from near the equator at 120°E and extending to 25°N near the dateline. The analysis for rainfall along the west coast of India shows a pattern (Fig. 6b) similar to that for rainfall over central India (Fig. 6a), but with smaller correlation coefficients.

For the late monsoon (September 20–October 15) sea-son rainfall, correlations with SSTs again show the familiar ENSO pattern (Fig. 6c, d). Late season monsoon rainfall over both central India and the west coast correlates nega-tively with August SSTs over the equatorial Pacific (Fig. 6c, d). With $r < -0.4$, these correlations are stronger than those for early monsoon rainfall (Fig. 6a, b), but the positive correlations along the band from near the equator at 120°E–25°N at the dateline are the weaker. This is consistent with the understanding that ENSO progressively strengthens during the summer season and thus, so does the teleconnection response. Correlation maps (not shown) of April (August) SSTs with early (late) seasonal AISMR, computed as spatial averages of gridded daily rainfall data of Rajeevan et al. (2006) resemble the amalgam of patterns in Fig. 6 but are closer to the patterns for central India.

The tropical Pacific SST signal appears to be prominent in a narrow window (May 20–June 15) at the start of the
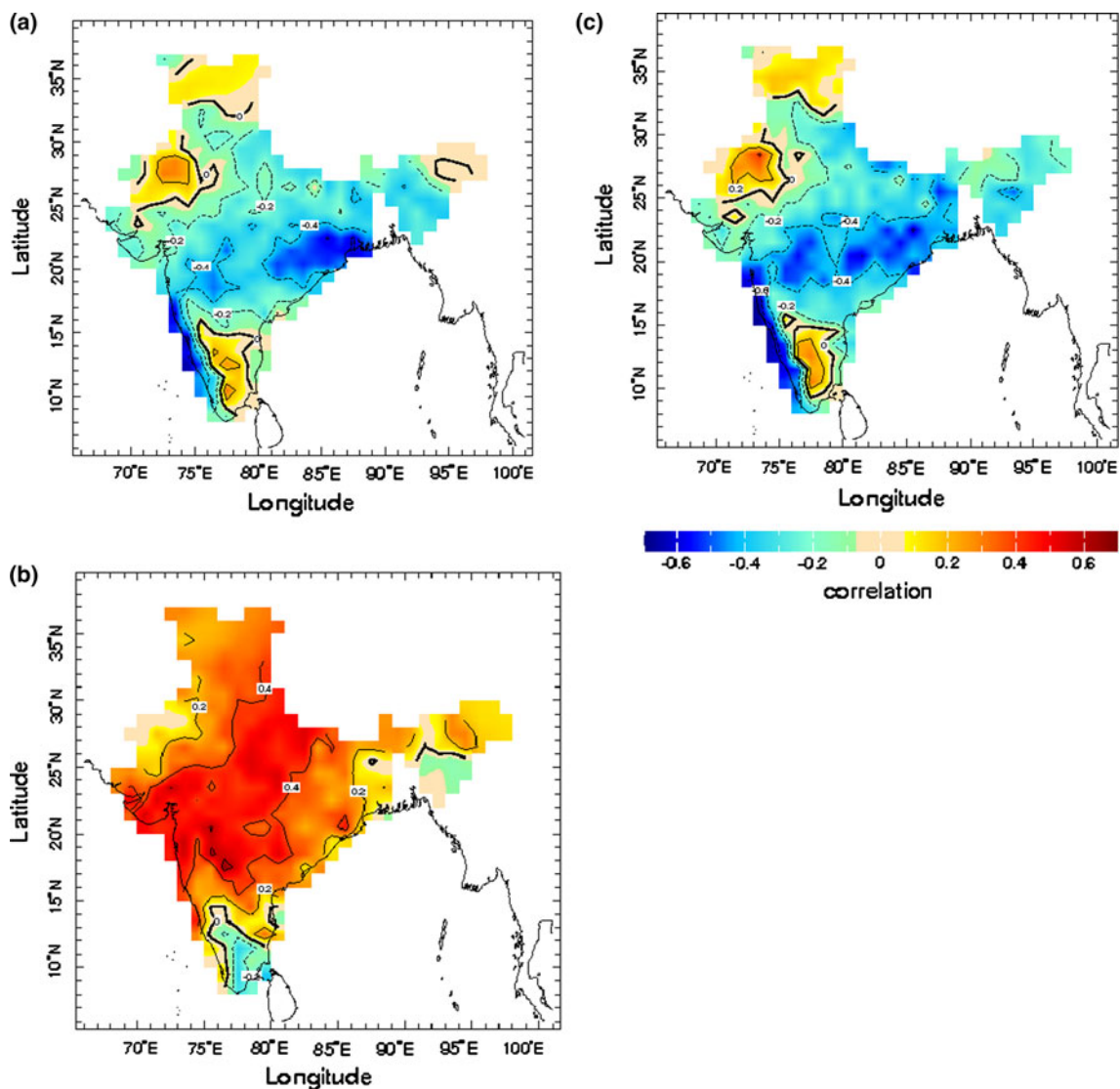
**Fig. 5** Correlation maps of **a** gridded rainfall (Rajeevan et al. 2006) with GX05 onset dates for the period 20 May to 15 June, **b** GX05 withdrawal dates with gridded rainfall for the period 20 September to 15 October, and **c** GX05 onset dates with number of days rainfall exceeding 2.5 mm during the period 20 May to 15 June, using the gridded rainfall dataset of Rajeevan et al. (2006)

monsoon season, but not, as noted earlier, for the entire monsoon season, at least since ∼1980. As an example, when we correlate May SSTs with rainfall in central India or along the west coast during a slightly later window (June 15–July 1), this signal is absent in both the regions (Fig. 7).

Others have shown that correlations of AISMR or related measures of Indian monsoon rainfall with ENSO tend to be stronger before 1980 than since that time (e.g. Feng and Hu 2004; GX05; Krishna Kumar et al. 1999, 2006). So, we examined correlations of early and late monsoon rainfall over central India and the west coast with SSTs for two periods, 1950–1980 and 1981–2008 (Figs 8, 9). Results for the early monsoon season show a trend opposite to that found for AISMR. Although SSTs in the central equatorial Pacific correlate negatively with early

monsoon rainfall in both central India and the west coast (Fig. 8), and positively along the band from near the equator at 120°E–25°N at the dateline, correlations for both regions have become stronger in the more recent period (Fig. 8c, d) than in the earlier period (Fig. 8a, b). Nevertheless, magnitudes of correlations for both periods reach, if not exceed, 0.4. For late monsoon rainfall (Fig. 9), the trend in the pattern is similar to that for AISMR; negative correlations of rainfall in both central India and along the west coast are larger in the central equatorial Pacific during the early period from 1950 to 1980 (Fig. 9a, b) than in the later period from 1981 to 2008 (Fig. 9c, d).

The absence of a correlation between ENSO indices and AISMR since 1981 but sustained correlations for early and late monsoon rainfall may reflect a growing influence of

**Fig. 6** Correlation maps of
SSTs with rainfall amount in
different parts of India in
months preceding early (**a**,
**b**) and late (**c**, **d**) monsoon
seasons for the period
1951–2008: April SSTs
correlated with average early
monsoon season (May 20–June
15) rainfall in **a** central India
(15°N–30°N; 70°E–85°E) and
**b** along the west coast of India
(0°N–20°N; 65°E–76°E), for the
period 1951–2008; and August
SSTs correlated with average
late monsoon season
(September 20–October 15)
rainfall in **c** central India, and
**d** along the west coast of
Western India
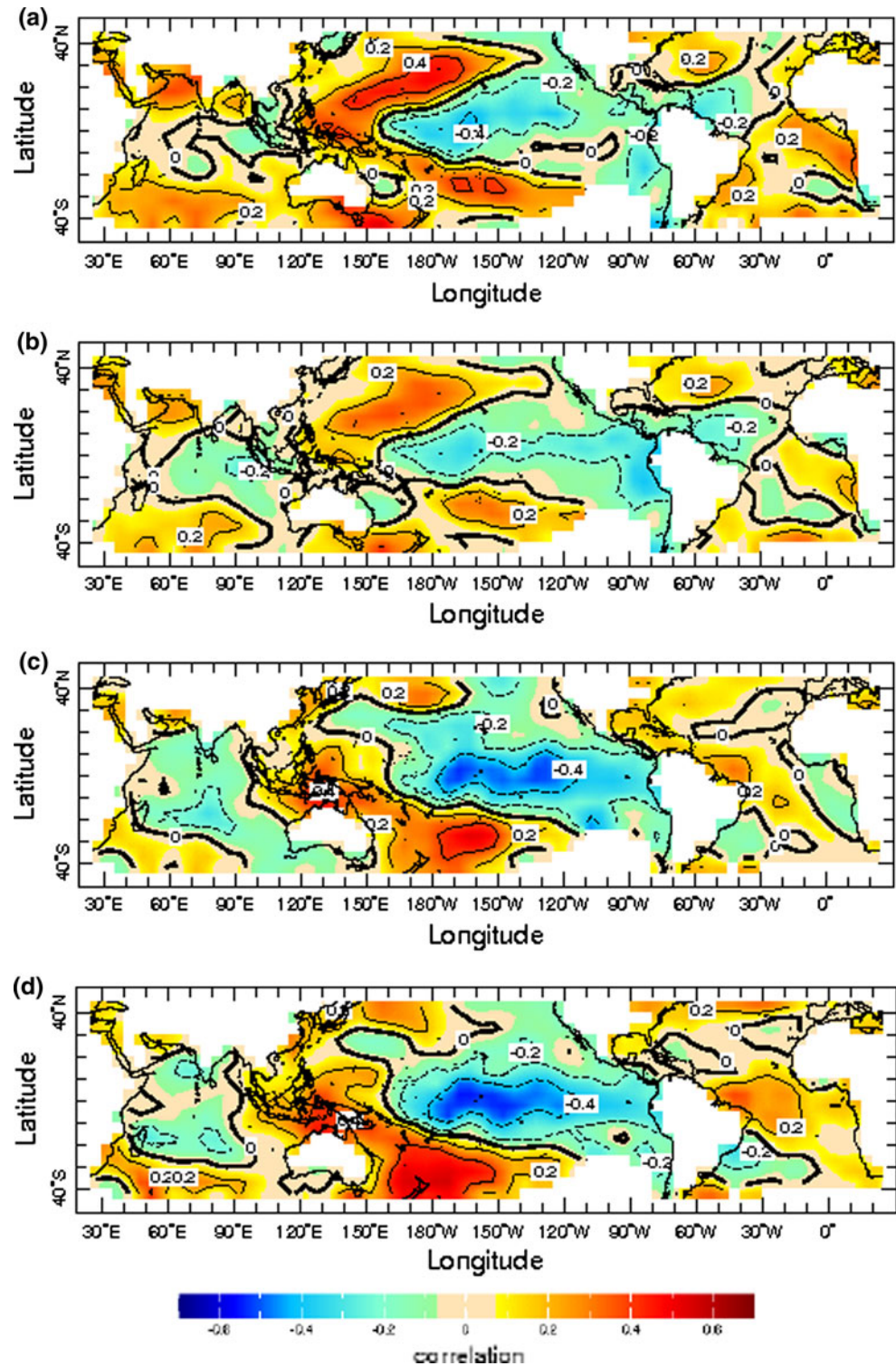


local conditions near and over India on rainfall during the
main part of the monsoon. As shown for late June (Fig. 7),
there is no correlation with ENSO. Thus we can imagine,
but have not shown, that central Pacific SSTs play a key
role in monsoon precipitation when local influences are

weak, but during the periods of heaviest rainfall, ENSO's
influence is weakened if not overwhelmed.

For both regions, for both early and late monsoon sea-
sons, and for pre- and post-1980 periods, the negative
correlations in the equatorial Pacific are largest near the

**Fig. 7** Correlation maps of May SSTs with average early monsoon season rainfall (June 20–July 1) rainfall for the period 1951–2008 for **a** central India (15°N–30°N; 70°E–85°E) and **b** along the west coast of India (0°N–20°N; 65°E–76°E)
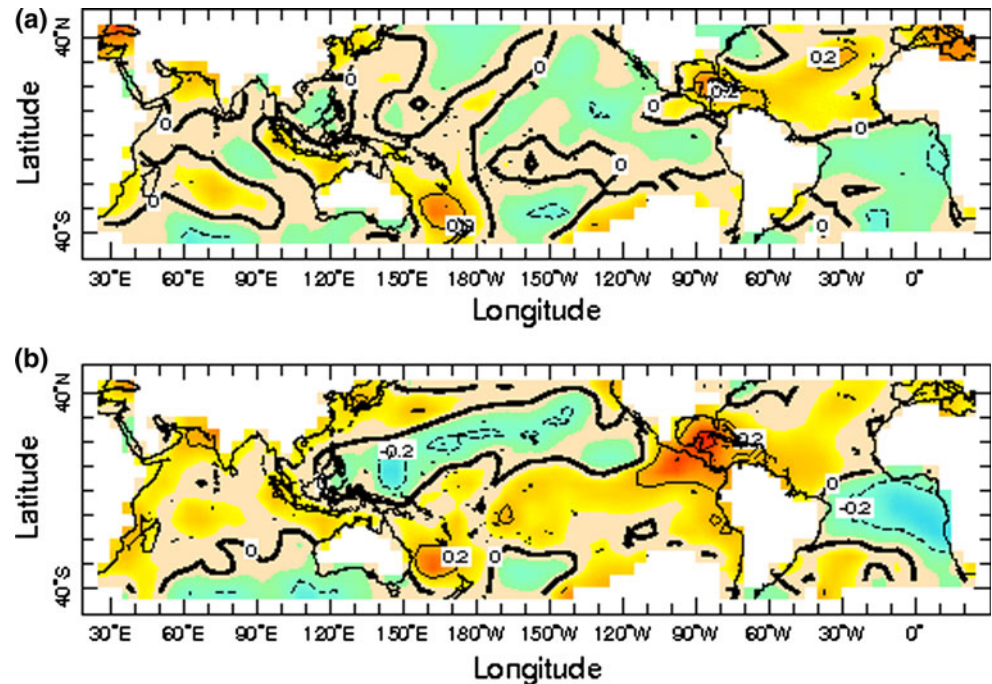


dateline, and for many of these cases, correlations in the eastern equatorial Pacific are weak (Figs. 8, 9). This suggests that at least for the early and late monsoon seasons, the part of the equatorial Pacific that seems to have the most influence on monsoon rainfall is the central equatorial Pacific, closer to the Niño4 than Niño3 region. It is interesting to note that as the association of AISMR with ENSO has weakened in recent decades (Krishna Kumar et al. 1996), the early and late season rainfall over western and central India have maintained their ENSO connection.

## 4 Predictions of early and late monsoon rainfall over western and central India

From the discussion above it seems clear that Pacific Ocean SSTs can potentially be used to predict the west-coast and central Indian rainfall during the early and late monsoon seasons. To demonstrate this, we first created predictors of the rainfall from regions of high correlation in Fig. 6. For the early monsoon rainfall in central India, Fig. 6 shows large correlations, of opposite sign, with April SSTs in the regions defined by 30–40°N, 170°E–170°W and by 5°S–5°N, 180°–160°W; hence, the difference in SSTs in these two regions offers a predictor for early monsoon rainfall amount. Similarly, for rainfall in west India, the predictor was developed using the difference in SSTs in two regions: 10–30°N, 150°E–190°W and 5°S–5°N, 180°–200°W. For the late season rainfall in both these regions August SSTs in the region of 5°S–5°N, 180°–220°W show the strongest correlation, and we use it as the predictor.

For the two regions, we linearly regressed (Helsel and Hirsch 2002) the early and late monsoon season rainfall and their respective predictors. Fig. 10a, b show the observed rainfall (in black) and the calculated estimates (red) for the early monsoon period. Calculated values match the variability better ($R^2 = 0.18$) than they estimate the extreme values, and the predictions for central India are better ($R^2 = 0.22$) than those for the west coast. To test the predictors further, we regressed data and predictors using data for 1951–1980 and used that fit to 'blind forecast' the rainfall in the 1981–2008 period (shown in blue). It can be seen that this blind prediction offers a fit comparable to, and perhaps better than, that using the data from the entire period (red line), which indicates that much of the skill (west India, $R^2 = 0.20$ and central India, $R^2 = 0.30$) is provided by the strong correlation with SSTs in the 1951–1980 period (Fig. 8). Figure 10c, d show similar results for the late season rainfall; using regressions for the entire period, for the west coast, $R^2 = 0.27$, and for central India, $R^2 = 0.23$, and for the blind predictions using data from 1950 to 1980 to predict 1981–2008, for the west coast, $R^2 = 0.30$, and for central India, $R^2 = 0.20$. We found similar skills ($R^2 = 0.25$) for both the fit and the blind forecast and for the forecast of early and late monsoon season all India rainfall, computed as an average of daily rainfall from the gridded data of Rajeevan et al. (2006).

To quantify the performance of these predictors, we conducted a bootstrap cross-validation. In this, 15% of observed rainfall amounts ($\sim$10 points representing 10 years) were dropped at random, and the remaining data

**Fig. 8** Correlation maps of April SSTs with early season (May 20–June 15) rainfall for the period 1951–1980 **a** in central India (15°N–30°N; 70°E–85°E) and **b** along the west coast of India (0°N–20°N; 65°E–76°E), and for the period 1981–2008 **c** in central India and **d** along the west coast
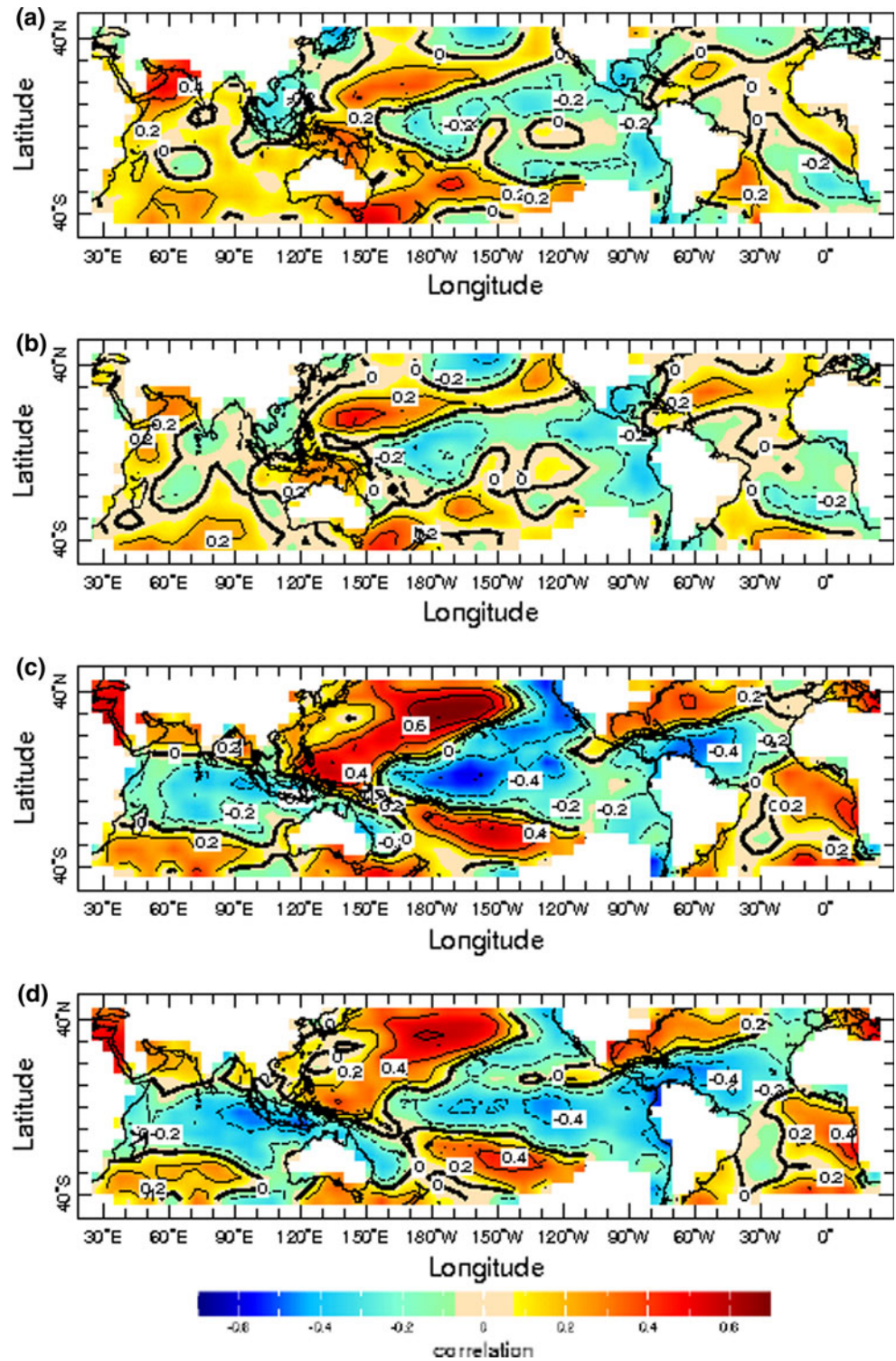


were fitted and used to predict those not used. The correlation, root-mean-squared error (RMSE), and forecast skill with respect to climatology (see equation below) were computed, and this was repeated 500 times to obtain an ensemble of estimates for each measure of skill. As a measure of skill, we use:

$$\text{forecast skill} = 1 - \text{MSE}_{\text{forecast}}/\text{MSE}_{\text{climatology}}$$

where $\text{MSE}_{\text{forecast}}$ and $\text{MSE}_{\text{climatology}}$ are mean squared errors of the forecast and climatology respectively for each set of 10 dropped years.

Figure 11 shows the boxplots of the skill measures for the early and late season cross-validated rainfall forecasts

**Fig. 9** Correlation maps of August SSTs with early season (September 20–October 15) rainfall for the period 1951–1980 **a** in central India (15°N–30°N; 70°E–85°E) and **b** along the west coast of India (0°N–20°N; 65°E–76°E), and for the period 1981–2008 **c** in central India and **d** along the west coast
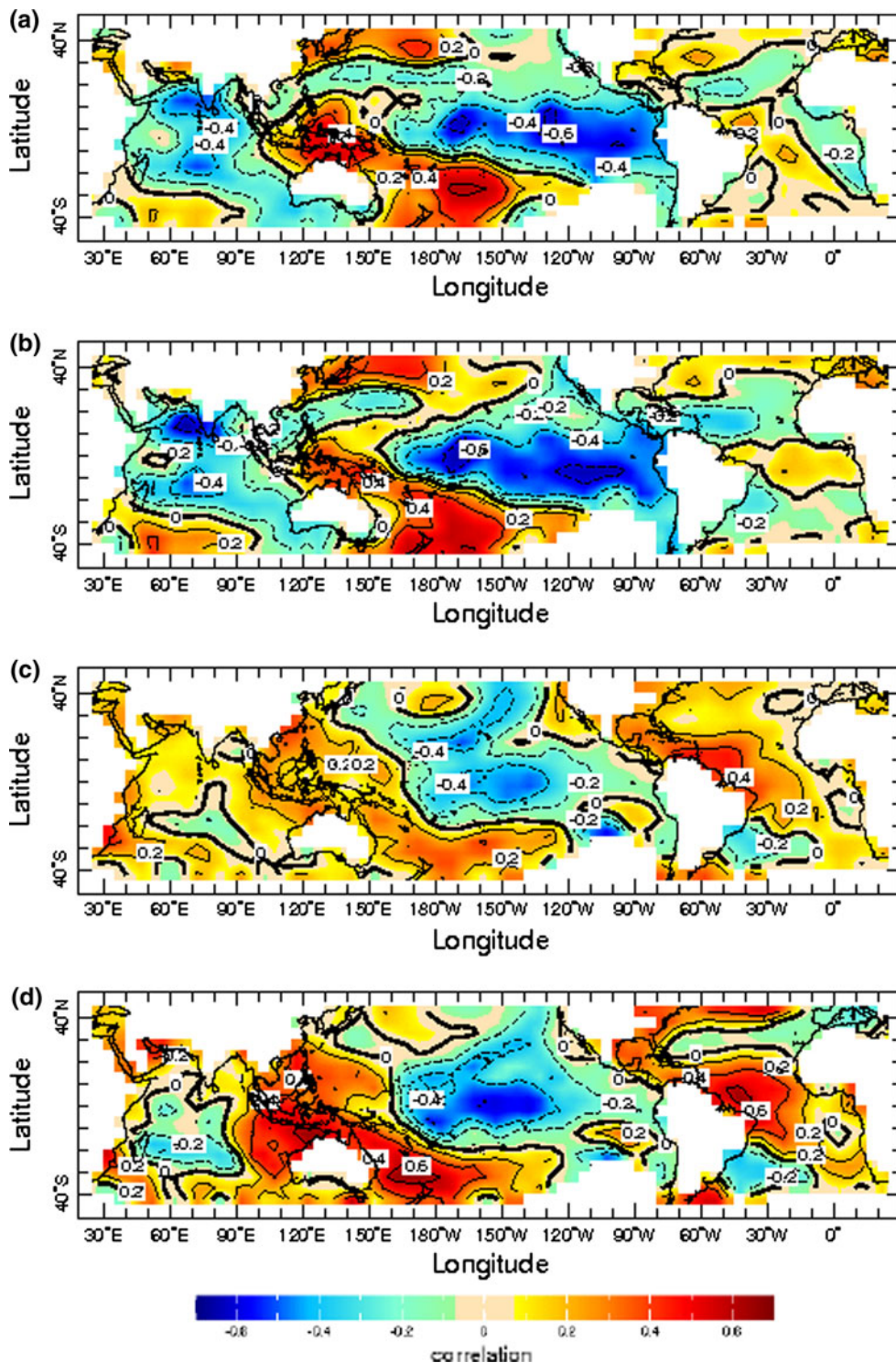


for the two regions. The median values of RMSE when scaled to standard deviations in rainfall amount for the two regions and for early and late monsoon seasons (dark lines in Fig. 11a) are comparable, but central India in the early season shows slightly more variability than the others. All four pairs of regions and seasons display similar correlation coefficient between observed and predicted with a median near 0.5 (Fig. 11b), which corresponds to correlations of rainfall amounts and predictors of $r \sim \pm 0.5$, and hence $R^2 \sim 0.25$. The median forecast skill with respect to climatology is positive and around 0.25 (Fig. 11c), which indicates that on average the forecasts are $\sim 25\%$ more

**Fig. 10** Time series showing measured and predicted rainfall in early (**a, b**) and late (**c, d**) monsoon seasons for two regions: the west coast of India (**a, c**) and central India (**b, d**). *Black lines* show measured early (**a, b**) and late (**c, d**) monsoon season rainfall, the areal average from gridded rainfall (Rajeevan et al. 2006). *Red lines* show predictions based on regressing all data, and *blue lines* show predictions of rainfall in 1981–2008 based on regressing only data prior to 1981
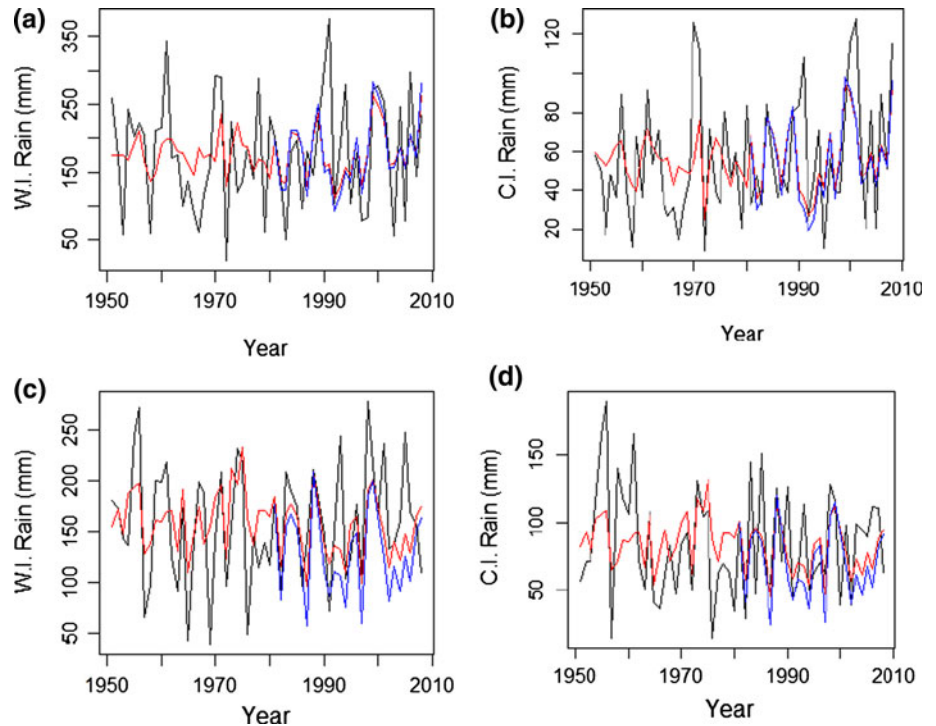


**Fig. 11** Boxplots of **a** scaled RMSE, **b** correlation, and **c** skill score with respect to climatology, from leave-ten out cross validation for early monsoon season rainfall on the west coast of India (*W.I–E*), late monsoon season rainfall on the west coast (*W.I–L*), early monsoon season rainfall in central India (*C.I–E*) and late monsoon season rainfall (*C.I–L*) in central India. *Dark lines* show median values, the *boxes* show the inter quartile ranges of the ensembles, the whiskers define the 5th and 95th percentiles, and *individual points* show values outside that range
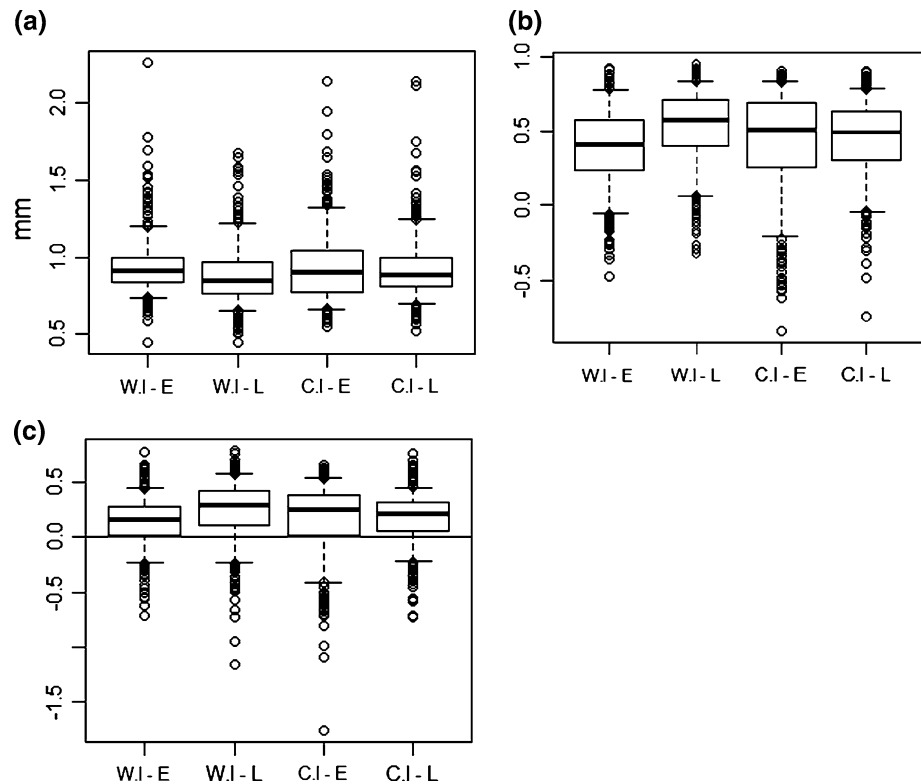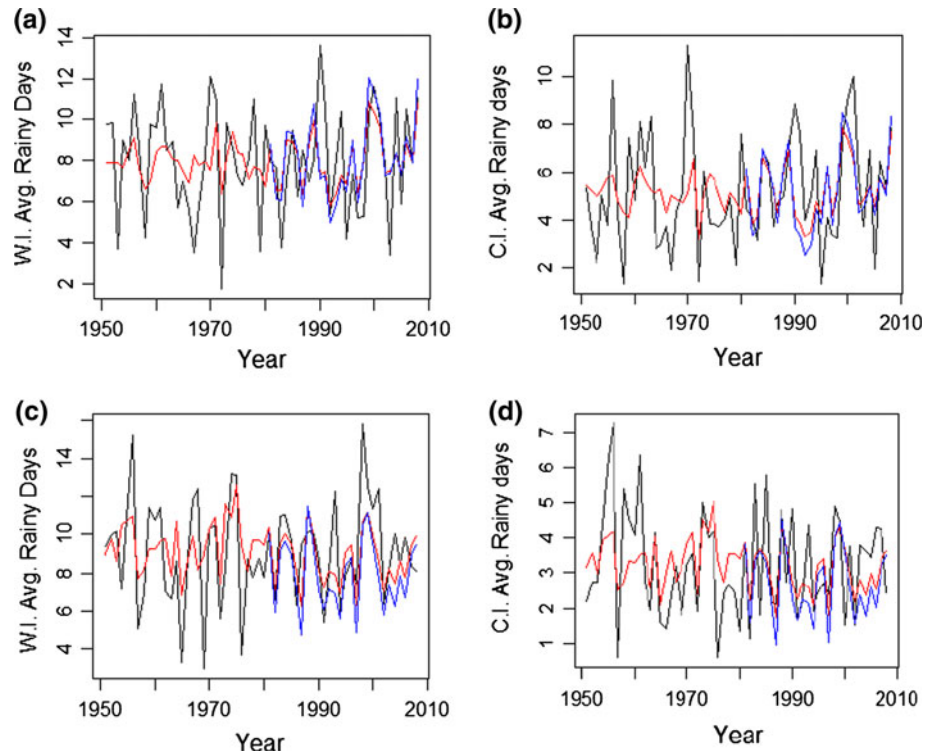


reliable than assuming that each year follows the climatological average.

We also attempted to forecast the number of days with extreme rainfall, which we define here as the days with rainfall greater than 2.5 mm/day, for the two regions and

the two periods, using the same predictors as for average rainfall. Again, we linearly regressed average numbers of days (back lines in Fig. 12) against SST predictors, and we obtained values of $R^2$ for early season average rainy days for west India and central India of 0.18 and 0.19,

respectively, and similarly for the late season values of
0.28 and 0.23. We then estimated the number of days of
heavy rainfall, using both SST predictors for the entire
period (red lines in Fig. 13) and those from 1950 to 1980 to
estimate the subsequent period from 1981 (blues lines).
The cross validation skill distributions (Fig. 13) are also
similar to those of seasonal rainfall amounts (Fig. 11).
These results indicate useful skill in predicting the average
number of rainy days during the early and late monsoon
season with a lead-time of 2–3 weeks—important for
agriculture planning. Categorical forecasts can also be
obtained using methods developed by Rajagopalan et al.
(2001). These forecasts can be combined with stochastic
weather generators and crop models to translate them to
crop related decision variables (e.g. Apipattanavis et al.
2010)

## 5 Summary and discussion

Whereas several factors influence seasonal rainfall amount
in India and contribute to its chaotic nature, SSTs in the
equatorial Pacific, the pattern associated with ENSO, seem
to be a dominant modulator of variability not only in onset
and withdrawal dates (e.g. Fasullo and Webster 2003;
GX05; Joseph et al. 1994), but also in rainfall amounts and
numbers of days of heavy rain in the early and late parts of
the monsoon season. For the early monsoon season (20
May–15 June), the difference between equatorial central

Pacific SSTs (5°S–5°N, 180°–160°W) and those farther
north (30–40°N, 170°E–170°W) in the preceding month of
April correlates with rainfall in both central India and on its
west coast (Figs. 5, 6a, b). Likewise for the late monsoon
season (20 September–15 October), similar combinations of
equatorial central Pacific SSTs and those farther north
(10–30°N, 150°E–190°W) in August correlate with rainfall
in these regions (Fig. 6c, d). Unlike the correlations of All
India Summer Monsoon Rainfall with various ENSO indi-
ces that have decreased in the past decades, these correla-
tions of April and August SSTs with early and late monsoon
rainfall have remained significant over the past six decades.
In fact, that for April SSTs and early monsoon rainfall has
become stronger in recent decades (Fig. 8). The region
common to all of the SST correlations lies near the dateline,
and hence seems to be better approximated by the Niño4
index than by either of the Niño3 and Niño3.4 indices.

We exploited these correlations to use SST combina-
tions in the Pacific Ocean in April and in August to predict
rainfall amounts and numbers of days of heavy rainfall
(>2.5 mm) in the early and late monsoon seasons. Various
tests of these predictors suggest that they can be used to
improve estimates of rainfall amounts and numbers of
rainy days by ∼25 and ∼20%, respectively, above amount
and numbers expected from average climatology. Other
forecasting methods could be employed to further exploit
the predictability (e.g. Rajeevan et al. 2007).

We recognize that the imperfect correlation of onset and
withdrawal dates with rainfall amount limits the social

**Fig. 13** Same as Fig. 11 but for average number days with extreme rainfall
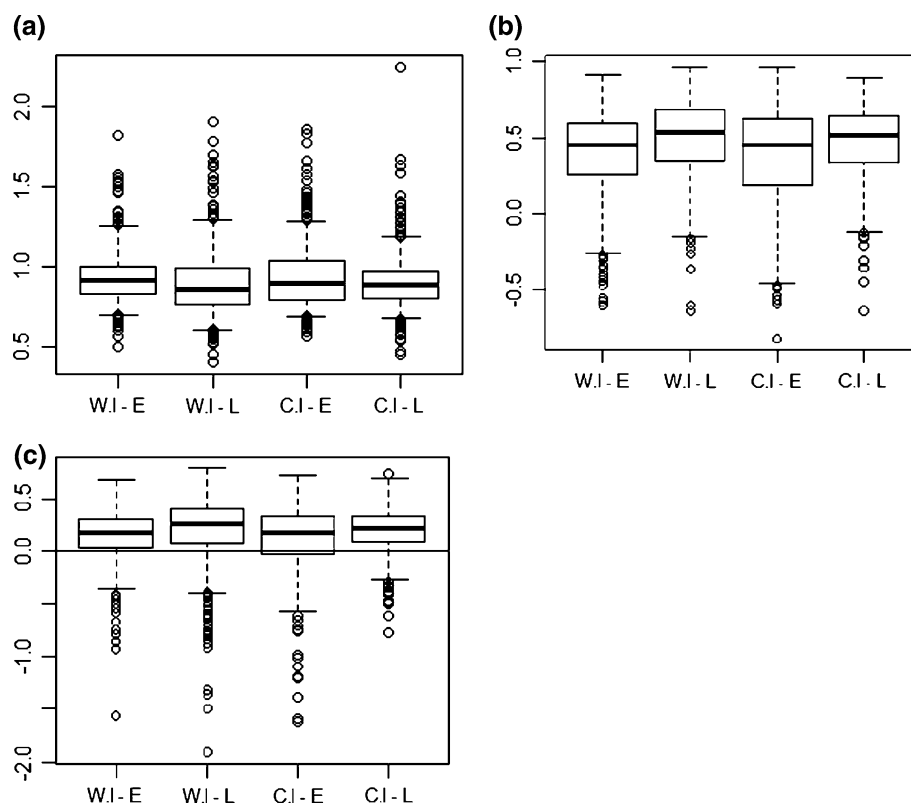


value of predictions of them, but we imagine that knowledge that the onset or withdrawal might be early or late should assist in agriculture and natural resources management, which is mostly rain-fed.

Despite the diminishing correlation of AISMR with ENSO as reported by earlier studies (e.g. Krishna Kumar et al. 1999, 2006), the early and late period rainfall attributes have maintained their ENSO correlations, especially those for the early season (Figs. 6, 8, 9). We suspect that the sustained correlations for the early season has occurred because the evolving influences of land surface and neighboring sea surface temperatures are less pronounced at the start of the monsoon than once the monsoon season has begun, but that these influences tend to become active soon after the monsoon is initiated. Consequently, in the early monsoon season, large-scale circulation associated with ENSO confronts a warm land surface over India with few complications, but once the monsoon has begun, the effects of rainfall on India, SSTs in the surrounding Indian Ocean, and other changing boundary conditions make ENSO only one factor among many that affect rainfall. The absence of any skill in predicting rainfall in late June (Fig. 7) presumably results from ENSO becoming a less important influence than other local ones.

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