

## Prediction of Indian rainfall during the summer monsoon season on the basis of links with equatorial Pacific and Indian Ocean climate indices

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## Environmental Research Letters



## LETTER

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## Abstract

Interannual variation of Indian summer monsoon rainfall (ISMR) is linked to El Niño-Southern oscillation (ENSO) as well as the Equatorial Indian Ocean oscillation (EQUINOO) with the link with the seasonal value of the ENSO index being stronger than that with the EQUINOO index. We show that the variation of a composite index determined through bivariate analysis, explains 54% of ISMR variance, suggesting a strong dependence of the skill of monsoon prediction on the skill of prediction of ENSO and EQUINOO. We explored the possibility of prediction of the Indian rainfall during the summer monsoon season on the basis of prior values of the indices. We find that such predictions are possible for July–September rainfall on the basis of June indices and for August–September rainfall based on the July indices. This will be a useful input for second and later stage forecasts made after the commencement of the monsoon season.

## 1. Introduction

During the colonial era, the Indian economy was described as being a gamble on the monsoon rains. Seasons with large deficits in the monsoon rainfall i.e. droughts, were often associated with famines. With planned development since independence, including substantive enhancement of irrigation and introduction of new crop varieties during the green revolution, there has been a rapid increase in food-grain production and a marked decrease in the contribution of agriculture to the gross domestic product (GDP). However, even today, irrigation is available for less than half of the cultivated land. Hence, the impact of severe droughts on the quantum of food-grain production is rather large and the impact on GDP has remained between 2 and 5% since the 1950s (Gadgil and Gadgil 2006). Furthermore, it has not been possible to get enhanced yields in good monsoon seasons because the farmers do not consider the investments in fertilizers and pesticides required to achieve this, to be cost effective in the absence of a

reliable forecast of good rainfall (Gadgil and Gadgil 2006). Thus prediction of the Indian summer monsoon rainfall (ISMR) and particularly its extremes (i.e. droughts with deficit in ISMR greater than one standard deviation and excess rainfall seasons with the positive ISMR anomaly larger than one standard deviation) continues to be extremely important even today.

The operational long-range forecasts of the summer monsoon (i.e. June–September) rainfall issued by the India Meteorological Department (IMD), the responsible government agency, have always been based on empirical/statistical models. At present, the new statistical models developed by Rajeevan *et al* (2007) based on the ensemble multiple linear regression and projection pursuit regression techniques are used for generation of the seasonal forecasts of ISMR. They have shown that the correlation of ISMR with the predictions of these models is very high, ranging from 0.78 to 0.88. Some of the predictors used are linked to the El Niño-Southern oscillation (ENSO), while others to different phenomena such as the North Atlantic

Oscillation, facets of the mid-latitude circulation and east Asian pressure pattern, which have been shown to be linked to monsoon variability (Rajeevan *et al* 2005). Predictions from atmospheric and coupled models are an additional input to the operational forecasts issued by IMD. In addition to the seasonal forecast of ISMR (being issued by the first week of June), IMD also issues forecasts for the all-India rainfall for part of the season, like July to September (i.e. after the culmination of the onset phase) during which 80% of the summer monsoon rainfall occurs and August–September (i.e. the latter half of the season) which accounts for about 50% of the seasonal rainfall. These forecasts of the expected rainfall during the remaining part of the summer monsoon season can be a valuable input for deciding on the appropriate farming strategy of crops to be cultivated and investments in fertilizers and pesticides. They are also useful for initiating required policy decisions on water resources, power generation and economy. These updates in forecasts assume particular significance when there is a large deficit in the rainfall of June as in 2009 and 2014, or monsoon fails in the first half as in 2002, and there is concern about whether preparations should be made to face a full-fledged drought.

Given the strong link between the ISMR and ENSO, manifested as an increased propensity for droughts during El Niño and for excess rainfall during La Niña (Sikka 1980, Pant and Parthasarathy 1981, Rasmusson and Carpenter 1983 and several subsequent studies (Rajeevan 2012 and references therein)), it was expected that the advances in prediction of ENSO with dynamical models would lead to a reasonable skill in the prediction of ISMR. However, prediction of ISMR proved to be a challenge for atmospheric models (Wang *et al* 2005, Gadgil *et al* 2005). In the last few years, a marked improvement in the skill of simulation/prediction of ISMR with coupled models is evident from the analysis of retrospective runs of the ENSEMBLES project (Delsole and Shukla 2012, Rajeevan *et al* 2012). The skill of the multimodel ensemble from ENSEMBLES is now reasonable (the correlation coefficient between predicted and observed ISMR for 1960–2005 being 0.45), although somewhat less than that of the latest statistical models (Gadgil and Srinivasan 2012); and the models are able to simulate/predict at least the sign of the ISMR anomaly in most of the extreme rainfall years. Despite the improvement in the performance of the coupled models, the skill of prediction of ISMR by these models is not, as yet, adequate. Thus, all the major models yield massive false alarms of droughts in the normal monsoon of 1997 and the excess monsoon season of 1983 (Nanjundiah *et al* 2013).

Our study attempts to develop simple empirical models for prediction for the rainfall averaged over the Indian region during the summer monsoon season, based on the present understanding of the interannual variation. The most important factor determining the

interannual variation of the monsoon rainfall and particularly the occurrence of extremes, is ENSO and in the recent past, several droughts (such as 1982, 1987 etc) have occurred during El Niño and excess rainfall during La Niña (such as 1988). A major exception was the strongest El Niño of the century in 1997, during which the monsoon rainfall was close to the mean, and it was suggested that the link of the monsoon with ENSO had weakened (Kumar *et al* 1999). However, a severe drought occurred during the subsequent relatively weak El Niño of 2002. Studies triggered by the intriguing behaviour of the monsoon in 1997 and 2002 have shown that the Equatorial Indian Ocean oscillation (EQUINOO) also plays an important role in the interannual variation of ISMR (Gadgil *et al* 2004, Ihara *et al* 2007). EQUINOO is an oscillation between a positive phase characterized by enhancement of convection over the western equatorial Indian Ocean (WEIO: 50°–70°E, 10°S–10°N) and suppression over the eastern part (EEIO: 90°–110°E, 0°–10°S), and a negative phase characterized by convection anomalies of the opposite sign over EEIO and WEIO. The positive (negative) phase of EQUINOO, which is associated with positive (negative) anomalies of rainfall over the Indian region, is characterized by easterly (westerly) anomalies in the zonal wind over the central equatorial Indian Ocean. While during the major drought of 2002, a negative phase of EQUINOO reinforced the adverse impact of the El Niño, the strong positive phase of EQUINOO played a critical role overcoming the negative impact of the strong El Niño in the normal monsoon season of 1997 and of a mildly unfavourable ENSO phase in the excess monsoon season of 1983 (Gadgil *et al* 2007).

It is interesting that EQUINOO played an important role in determining the rainfall in the season of 1997 as well as of 1983, in which large false alarms occurred in the model predictions. Many of the coupled models of ENSEMBLES and National Center for Environmental Prediction Climate Forecast System (NCEP CFS) versions 1 and 2, are not able to simulate/predict the phase of EQUINOO and almost no model able to simulate the link of EQUINOO with ISMR (Nanjundiah *et al* 2013). Thus, further improvement of the dynamical models is needed for better prediction of EQUINOO, its link with ISMR and hence the ISMR itself. The statistical models used at present at IMD also do not make use of the linkages of EQUINOO with the ISMR (Rajeevan *et al* 2007).

It is important to note that EQUINOO has been considered to be the atmospheric component of the Indian Ocean Dipole/Zonal Mode (IOD/IOZM) (Saji *et al* 1999, Webster *et al* 1999), just as the southern oscillation is the atmospheric component of the coupled ENSO mode over the Pacific. However, whereas there is a tight linkage between the southern oscillation in the atmosphere and the fluctuations between El Niño and La Niña in the ocean, with the southern oscillation index being highly correlated to the

different El Niño indices (e.g. correlation coefficient of 0.86 for the NINO3.4 index), the correlation between EQWIN and dipole mode index (DMI) is relatively low i.e., 0.53 for the period 1958–2004 (Gadgil *et al* 2007). While EQUINOO and the oceanic component of IOD are both characterized by positive phases for positive dipole events such as of 1994 and 1997, they have opposite phases for June–September in almost one third of the years (Gadgil *et al* 2007). In fact, in the first paper on IOD by Saji *et al* (1999) it was shown that the correlation between rainfall over the Indian region and the DMI, in the boreal summer is very poor. On the other hand, the correlation between the ISMR and EQUINOO is significant and explains 19% of the variance (Gadgil *et al* 2007).

In this paper, we assess the potential of using ENSO as well as EQUINOO to predict the rainfall averaged over the Indian region for the summer monsoon (i.e. ISMR) as well as over a part of the summer monsoon season, by investigating the links of ISMR as well as parts of the seasonal rainfall with simultaneous and preceding states of these modes. We examine whether using information/prediction of EQUINOO in addition to the information/prediction of ENSO, can improve the predictions beyond those generated with information/prediction of ENSO alone. Since, DMI is predicted by several models at present, we also assess whether incorporation of DMI along with ENSO would improve the skill of predictions beyond that with ENSO alone.

## 2. Data and indices

The following data sets for the period 1958–2010, were used in this study: (i) ISMR (Parthasarathy *et al* 1995) and updates from Indian Institute of Tropical Meteorology ([www.tropmet.res.in](http://www.tropmet.res.in)), (ii) NINO3.4 index (sea surface temperature (SST) anomaly over NINO3.4 (120°–170°W, 5°S–5°N) region) obtained from climate analysis section, National Center for Atmospheric Research, USA ([www.cgd.ucar.edu](http://www.cgd.ucar.edu)), (iii) surface wind data (Kalnay *et al* 1996) from National Center for Environmental Prediction ([www.cdc.noaa.gov](http://www.cdc.noaa.gov)) and (iv) DMI, the Indian Ocean DMI from [www.jamstec.go.jp](http://www.jamstec.go.jp).

To study the relationship of the monsoon rainfall with ENSO, we use an ENSO index based on the SST anomaly of the NINO3.4 region since it is better correlated with ISMR than the SST anomaly of the other NINO regions. The ENSO index is defined as the negative of the NINO3.4 SST anomaly (normalized by the standard deviation), so that positive values of the ENSO index imply a cold phase of ENSO which is favourable for the monsoon. Throughout this paper, we use the word favourable phase of either of the modes ENSO and EQUINOO to imply that phase which is favourable for the Indian monsoon. We have verified the robustness of the results presented here vis

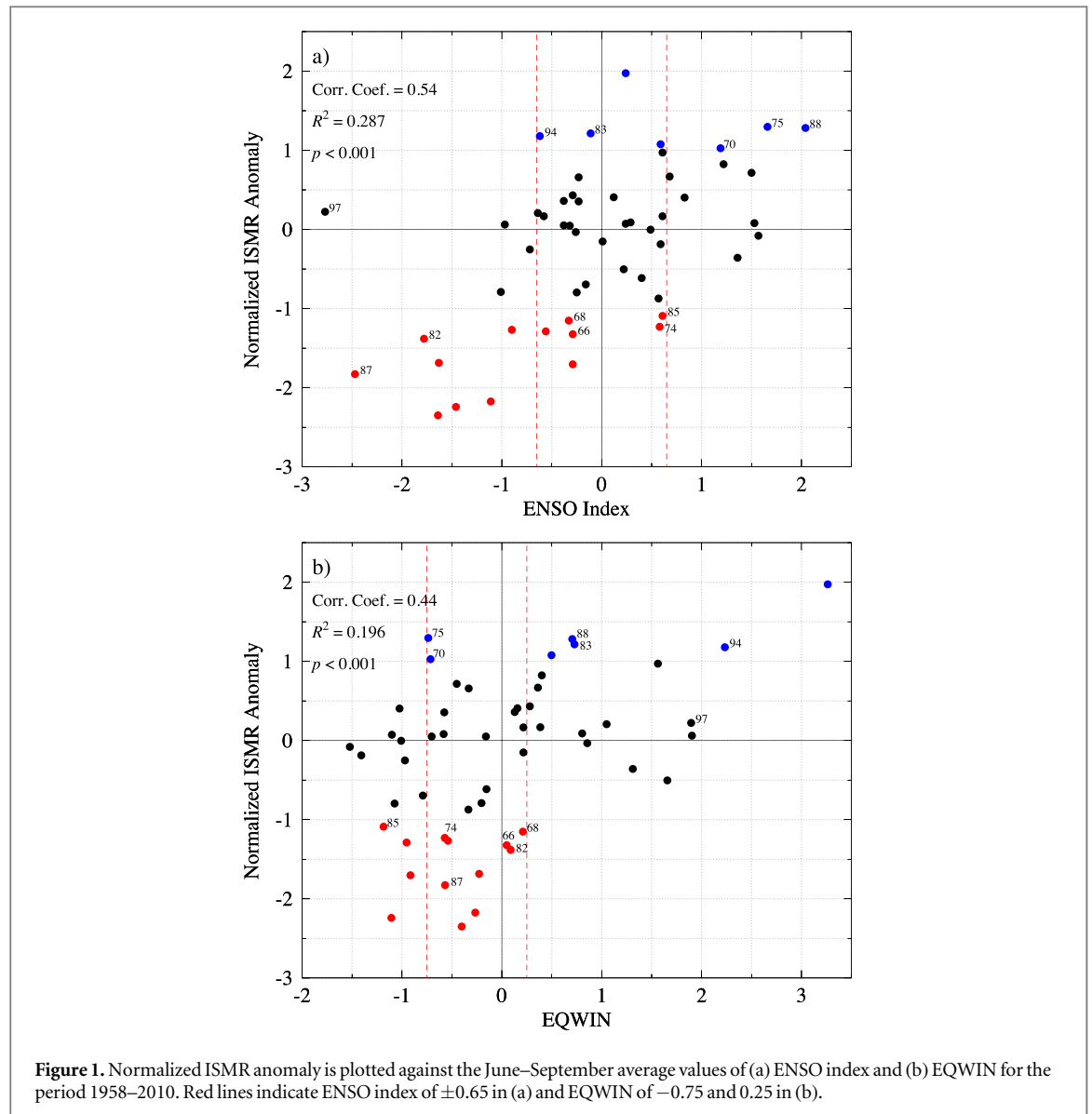
à vis the SST data set used, by showing that the results hardly change when alternative data sets viz. Hadley Centre Sea Ice and SST data set (HadISST, Rayner *et al* 2003) or Extended Reconstructed SST (ERSST, Smith *et al* 2008) data sets are used. El Niño is associated with ENSO index less than  $-1.0$  and La Niña with ENSO index greater than  $1.0$ . We use an index of EQUINOO based on the anomaly of the zonal component of the surface wind at the equator (60°E–90°E, 2.5°S–2.5°N). The zonal wind index (henceforth EQWIN) is taken as the negative of the anomaly of the zonal wind so that positive values of EQWIN are favourable for the monsoon (Gadgil *et al* 2004). Saji *et al* (1999) had chosen a slightly different region for surface wind index i.e. (70°E–90°E, 5°S–5°N). However, the results presented are not sensitive to this change in the region over which the wind is averaged since the variation of the wind over these two regions is highly correlated (correlation coefficient of 0.96).

## 3. Association of the rainfall during the summer monsoon season with ENSO, and EQUINOO and IOD

### 3.1. Summer monsoon season

The relationship of ISMR with ENSO index (during JJAS) is shown in figure 1(a). It is seen that this association is rather strong, explaining about 29% of the variance of ISMR. Note that there are no droughts for ENSO index greater than 0.65 (which includes all La Niña events) and no excess rainfall seasons for ENSO index less than  $-0.65$  (which includes all El Niño events). Thus, if the magnitude of the ENSO index predicted is larger than 0.65, one-sided prediction of no droughts (if the prediction is for positive ENSO index) or of no excess rainfall season (if the prediction is for negative ENSO index) can be generated on the basis of this relationship. However, within the range  $-0.65 < \text{ENSO index} < 0.65$ , there is a very large variation in ISMR with several droughts and excess rainfall seasons as well. In particular, droughts of 1974 and 1985 occurred despite a favourable phase of ENSO and excess rainfall occurred in 1994 despite an unfavourable phase of ENSO.

The simultaneous relationship of ISMR with EQWIN during JJAS (figure 1(b)) is not as strong as that with ENSO, explaining about 19% of the variance of ISMR. We note that while negative EQWIN is associated with a strengthening of the climatological east-west gradient in convection/precipitation over the equatorial Indian Ocean, positive EQWIN is associated with a weakening or reversal of the east-west gradient. For EQWIN larger than 0.25, there are no droughts and the chance of the rainfall being below the mean is less than 12%. On the other hand, for EQWIN less than  $-0.75$ , there are no excess rainfall seasons and hence as for ENSO, one-sided predictions for the extremes are possible for sufficiently large or small



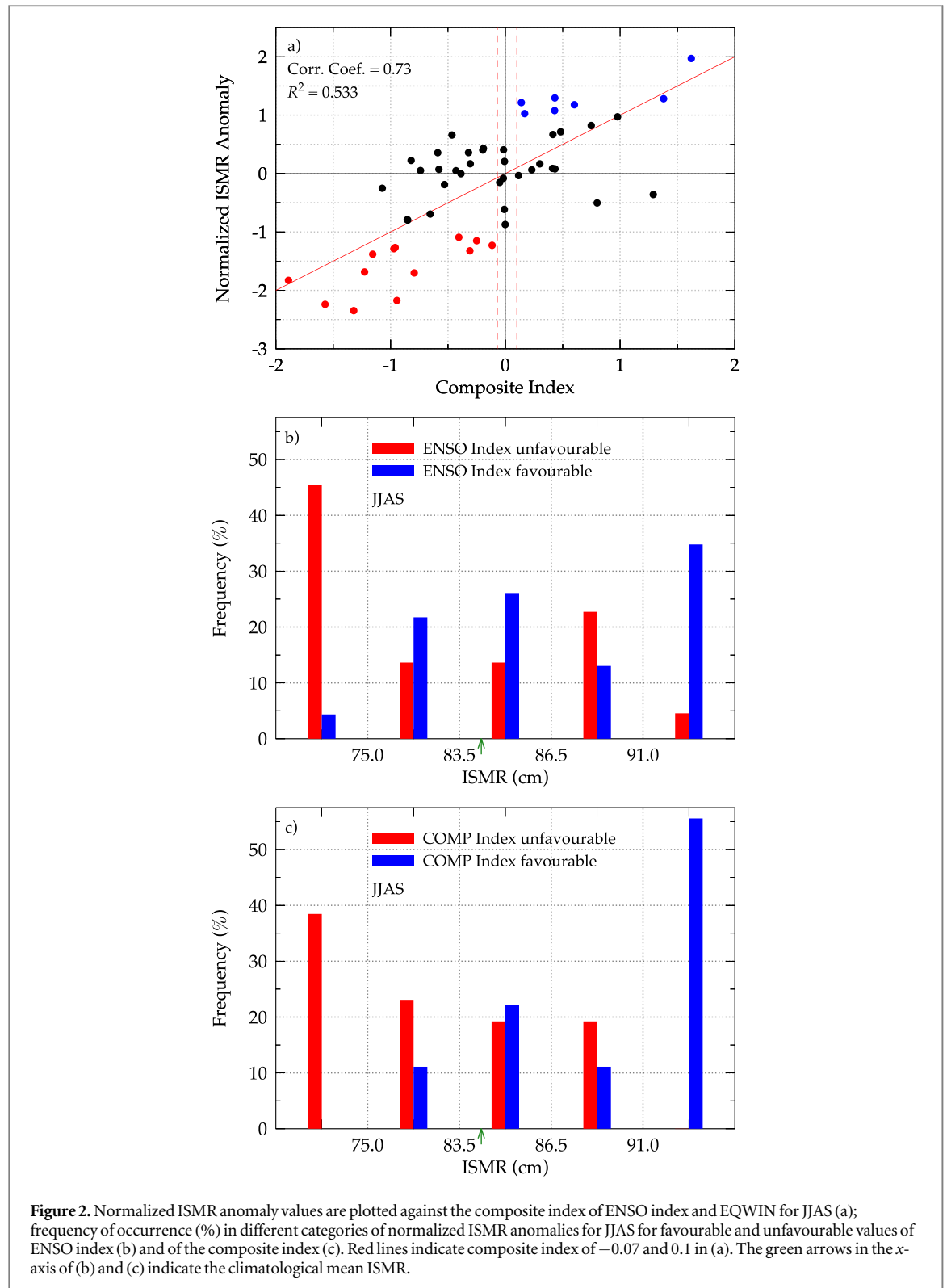
EQWIN values. However, there is a large variation of ISMR within the range  $-0.75$  to  $0.25$ . In particular, the droughts of 1966, 68 and 82 occurred despite favourable EQUINOO, and excess rainfall occurred in 1970 and 1975 despite an unfavourable EQUINOO.

A prominent feature of the relationship between ISMR and EQWIN, is the marked asymmetry between positive and negative EQWIN, with a much larger range of variation of ISMR for negative values of EQWIN than for positive values of EQWIN. The distribution of EQWIN is positively skewed, with the median at  $-0.2$  which is less than the mean of  $0.0$ . This implies that the tail of positive EQWIN values is long relative to that of negative EQWIN values with much stronger anomalies of positive than negative EQWIN. Such an asymmetry is also seen between the positive and negative phases of IOD events and the differences in their evolution and impact (e.g., Hong *et al* 2008, Cai *et al* 2012). Ng *et al* (2014) show that a positive IOD tends to have stronger cold SST anomalies over the

eastern Indian Ocean with greater impacts than warm SST anomalies that occur during its negative phase.

The relationship between ISMR and DMI is rather weak, with the correlation coefficient not significantly different from zero, and only about 1% of the variance of ISMR explained by the variance of DMI ( $R^2 = 0.01$ ,  $p$ -value =  $0.502$ ), consistent with previous studies (Saji *et al* 1999). Thus, if we consider the coupled atmosphere–equatorial Indian Ocean system, the variation of ISMR appears to be related to the state of only the atmospheric component i.e. EQUINOO.

It should be noted that for the summer monsoon season, EQWIN is poorly correlated with the ENSO index (table 2,  $R^2 = 0.01$ ,  $p$ -value =  $0.455$ ). Hence we expect the fraction of the ISMR variance explained when ENSO and EQUINOO are taken together, to be larger than that explained by ENSO alone. The simplest model based on the relationship of ISMR with ENSO and EQUINOO, is a linear multiple regression model for ISMR based on the ENSO index and EQWIN. From the data for 1958–2010, this is



obtained as:

$$\text{ISMR}_{\text{model}} = \text{Composite index} = 0.58 \\ \times \text{ENSO index} + 0.5 \times \text{EQWIN} - 0.16.$$

The variation of the observed ISMR with this composite index is shown in figure 2(a). It is seen that, there are no droughts for positive values of the composite index and no excess rainfall seasons for negative values. A band around the value of zero of the composite index

separates the extremes in figure 2. Thus if it is possible to predict ENSO as well as EQWIN, and hence the composite index, it is always possible to generate a one sided prediction for the extremes, either for no droughts or for no excess rainfall, on the basis of this relationship. This is consistent with the result of Gadgil *et al* (2004) for 1958–2003, that in the phase plane of the indices of the ENSO and EQUINOO modes, the droughts are well separated from the excess rainfall.



**Table 1.** Correlation coefficients of the all-India rainfall (AIR) for the whole and parts of summer monsoon season, with simultaneous and prior values of ENSO index, EQWIN, DMI and multiple correlation coefficients for indices of ENSO, EQUINOO and of ENSO, IOD for the period 1958–2010. Correlations significant at 95% level are highlighted.

Rainfall (AIR) for the period	Indices for the period	Corr. coeff. with ENSO index	Corr. coeff. with EQWIN	Multiple correlation coefficient ENSO index and EQWIN	Corr. coeff. with DMI	Multiple correlation coefficient ENSO index and DMI
JJAS	JJAS	<b>0.54</b>	<b>0.44</b>	<b>0.73</b>	−0.10	<b>0.55</b>
JAS	JAS	<b>0.54</b>	<b>0.38</b>	<b>0.73</b>	−0.14	<b>0.55</b>
AS	AS	<b>0.47</b>	0.29	<b>0.61</b>	−0.11	<b>0.49</b>
JJAS	May	0.21	0.12	0.23	−0.05	0.21
JAS	June	<b>0.36</b>	<b>0.41</b>	<b>0.49</b>	−0.19	<b>0.38</b>
AS	July	<b>0.45</b>	<b>0.34</b>	<b>0.61</b>	0.02	<b>0.48</b>

**Table 2.** Inter-correlations between the indices for different parts of the season.

Period	ENSO index with EQWIN	ENSO index with DMI
JJAS	−0.10	<b>−0.42</b>
JAS	−0.18	<b>−0.44</b>
AS	−0.19	<b>−0.49</b>
May	0.11	−0.18
June	0.24	−0.24
July	−0.15	<b>−0.30</b>
July + August	−0.19	<b>−0.35</b>

Considering EQUINOO as well as ENSO implies a better prediction for not just the extremes but for the entire range of ISMR. The multiple correlation of ISMR with the ENSO index and EQWIN is 0.73 which is much higher than that of ISMR with ENSO (table 1). Thus, ENSO and EQUINOO together explain more than 53% of the variance of ISMR whereas ENSO alone explained about 29% of the variance. On the other hand, the multiple correlation of ISMR with the ENSO index and DMI is 0.55 which is almost the same that of ISMR with the ENSO index. This is because DMI is well correlated with the ENSO index (table 2) and hence when ENSO index and DMI are considered together, the variance explained is not much larger than that explained by ENSO alone (table 1). These results are consistent with those of Ihara *et al* (2007) who investigated the relationship between ISMR and ENSO, EQWIN and DMI for the period 1881–1998, and showed that the linear reconstruction of ISMR on the basis of a multiple regression from the ENSO index (taken as NINO3) and EQWIN better specifies the ISMR than the regression with only NINO3, whereas no skill is added when DMI is considered along with ENSO.

We consider next the impact of the knowledge/prediction of just whether the ENSO index or the composite index is favourable or unfavourable on the frequency distribution of the monsoon rainfall. Whether ENSO index is favourable or unfavourable for ISMR depends on the sign of the index. However, when the index is very close to zero, small errors in the data can lead to a change in the sign of the index and hence to wrong deductions about whether it is

favourable or not. We, therefore, take the index to be unfavourable (favourable) for values  $< -0.15$  ( $> 0.15$ ). This implies that the index is unfavourable when the NINO3.4 SST anomaly is larger than 15% of the standard deviation, since the indices are normalized. Similarly the composite index is considered to be favourable when the value is greater than 0.15 and unfavourable when it is  $< -0.15$ . Five categories of rainfall are chosen large deficit (i.e.  $< 75$  cm), deficit (between 75 and 83.5 cm), normal (between 83.5 and 86.5 cm), above normal (between 86.5 and 91.0 cm) and large excess ( $> 91.0$  cm) so that, when all the years are considered, the frequency of occurrence in each category is  $\sim 20\%$ . The frequencies in these categories for cases of favourable ENSO (ENSO index  $> 0.15$ ) and unfavourable ENSO (ENSO index  $< -0.15$ ) as well as for the favourable composite index ( $> 0.15$ ) and unfavourable composite index ( $< -0.15$ ) are shown in figure 2(b). It is seen that the impact of ENSO is rather large on the frequency of occurrence in categories with the highest and lowest rainfall. The chance of large deficits increases from 20% to 45%, while that of large excess decreases from 20% to less than 5% for unfavourable ENSO index. On the other hand, the chance of large excess increases from 20% to 35% and chance of large deficit decreases from 20% to less than 5% for favourable ENSO index. When information on EQWIN is also incorporated and the composite index is considered, the impact on the lowest and highest rainfall categories is even higher with the chance of large deficits for positive values of the composite index and large excess for negative value, being zero. In that case, there is hardly any impact on the chance of rainfall around the median.

Thus, the strong relationship of ISMR with simultaneous values of ENSO and EQUINOO indices can lead to reliable predictions of ISMR (with over 50% of the variance explained) if ENSO and EQUINOO can be predicted. It is seen (figure 2(c)) that there is a discernible impact on the predicted frequencies of the lowest and highest rainfall categories. At present ENSO can be predicted with average correlation skill of 0.65, ahead of the summer monsoon season (Barnston *et al* 2012). For generating predictions of EQUINOO, more work is needed on the models used for

seasonal prediction. If and when such predictions become available, it will become possible to generate predictions of ISMR with reasonable skill as well as predictions of the non-occurrence of extremes in every case.

### 3.2. Rainfall during July–September, August–September

An analysis of the relationship of the all-India rainfall during July–September and August–September with the indices of the two modes suggests that while the relationship with simultaneous values of ENSO index is comparable to the June–September case that with EQUINOO is somewhat weaker (table 1). As for the summer monsoon season, the ENSO index is poorly correlated with EQWIN for these periods as well (table 2). Hence the multiple correlation is much higher than the correlation with ENSO index and a large fraction of the variance of the Indian rainfall during these periods is explained when ENSO and EQUINOO are considered together. On the other hand, DMI is well correlated with ENSO and when DMI and ENSO are considered together, DMI does not add to the variance explained by ENSO alone (table 1). When ENSO and EQUINOO are considered together, 53% of variance of the July–September rainfall is explained, while for August–September rainfall, 37% of the variance explained. In all the cases, the variance added by incorporating EQWIN to the variance contributed to ENSO alone is statistically significant at 90%.

Thus, if reliable predictions of the ENSO index and EQWIN for July–September and August–September can be generated using dynamical models, the Indian rainfall for these periods can be predicted on the basis of this association.

## 4. Prediction of all-India rainfall

We explored the possibility of predicting ISMR, the all-India rainfall during July–September and August–September, by using ENSO and EQUINOO indices for the month preceding the period for which the rainfall is predicted. The skill of this prediction obviously depends on the nature of the evolution of these two modes during May–September and hence the extent to which the value of either index can be predicted from the value prior to the period of interest.

The time-scale of the evolution of ENSO is several months and the ENSO index for any month is highly correlated with that of the previous month (figure 3). Furthermore, the ENSO index for June–September, July–September and August–September is well correlated with the index of the previous month (correlation coefficients 0.65, 0.86 and 0.95 respectively). Thus, it is possible to predict with some skill, whether ENSO will be favourable or unfavourable during the period of interest, on the basis of the prior value of the

ENSO index. The evolution of EQWIN is more complex (figure 3). The correlation between EQWIN for May (i.e. in the month just prior to the summer monsoon season) with EQWIN for June is not high (correlation coefficient 0.24), and the sign of EQWIN changes from May to June in 40% of the cases. Thus the evolution of EQWIN from May to June is governed to a large extent by factors other than the EQWIN in May. The relation of EQWIN to the state in the previous month gets steadily stronger during the summer monsoon with the number of cases with sign reversal finally decreasing to a little over 20%. The correlation coefficients of EQWIN for June–September, July–September and August–September with the index of the previous month are lower than the corresponding ones for the ENSO index, being 0.19, 0.45 and 0.56 respectively. Despite a reasonably strong relationship of the ENSO index for June–September with that of May, the correlation of the ISMR with the ENSO index of May is poor (table 1). The relationship of ISMR with the state of the EQUINOO during May is even weaker and that to the composite index based on these two indices also not strong enough for these indices to be used for prediction of ISMR (table 1).

Consider the prediction of the all-India rainfall for periods July–September and August–September using the values of EQWIN and ENSO index prior to that period. The July–September rainfall is significantly correlated with the ENSO index and EQWIN for the month of June and for the linear combination of these two indices determined by bivariate analysis i.e. the composite index (table 3). The August–September rainfall is even better correlated with July values of the indices (table 3). In each case, the correlation of the rainfall with the composite index is much higher (statistically significant at 90% level) than that from ENSO index alone. The variation of relationship of the July–September (August–September) rainfall with the composite index for June (July) determined by multiple linear regression is shown in figure 4(a) (figure 5(a)). ENSO and EQWIN together explain 24% and 37% of the variance of the July–September and August–September respectively. Further, it is possible to generate one-sided predictions for the non-occurrence of extremes and low probability of a particular sign of the rainfall anomaly for a certain range of values of the composite index. Thus, it is seen from figure 4(a) that if the value of the June composite index is larger than 0.12 (smaller than  $-0.27$ ), the chance of the July–September rainfall being deficit (above normal) is small and there are no droughts (excess rainfall seasons). When the July composite index (figure 5(a)) is larger than 0.12 (smaller than  $-0.12$ ), there are very few years with below (above) normal August–September rainfall and no droughts (excess rainfall seasons). The contingency table (table 4) shows a strong association of July composite index and August–September rainfall. Fisher's exact test (Fisher 1925, Freeman and



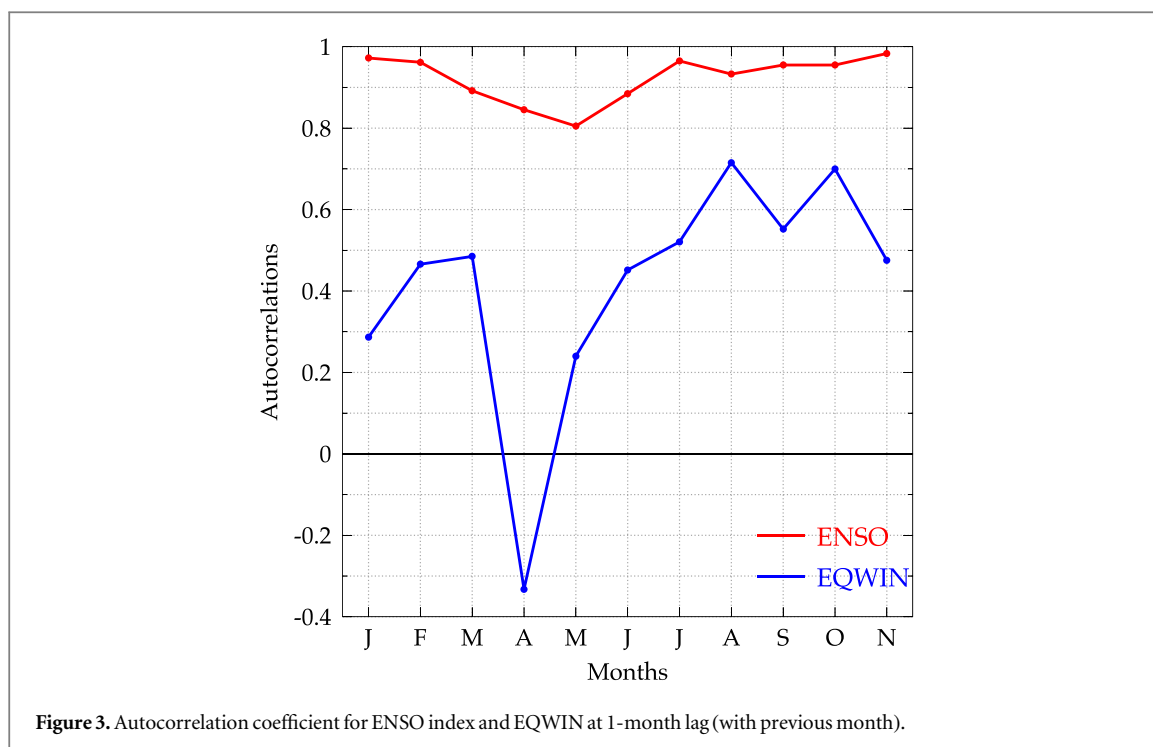


Figure 3. Autocorrelation coefficient for ENSO index and EQWIN at 1-month lag (with previous month).

Table 3. Reconstruction of ISMR and prediction of the all-India rainfall for different parts of the summer monsoon season based on the composite index using ENSO and EQWIN.

AIR for the period	Indices for the period	Composite indices
June–September	June–September	$0.58 \times \text{ENSO} + 0.5 \times \text{EQWIN} - 0.16$
July–September	June	$0.28 \times \text{ENSO} + 0.35 \times \text{EQWIN}$
August–September	July	$0.51 \times \text{ENSO} + 0.41 \times \text{EQWIN} - 0.02$

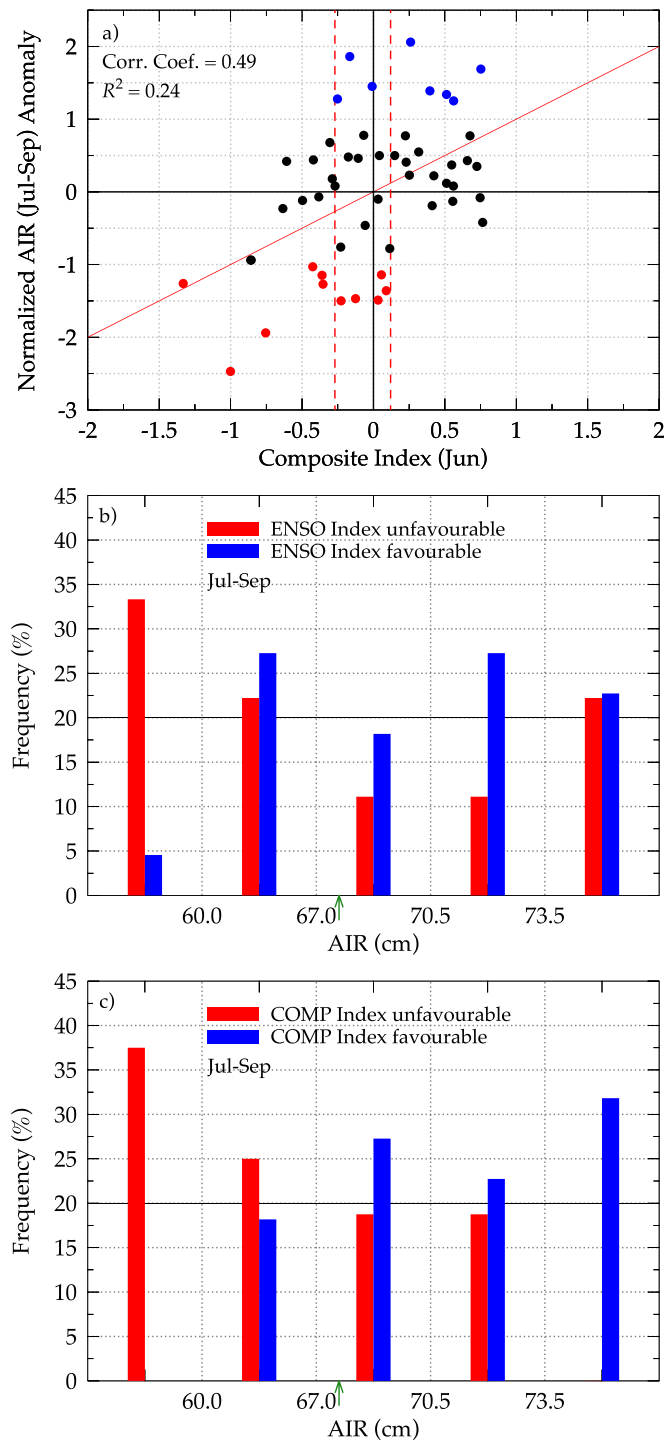
Halton 1951) reveals that the association is statistically significant at 99% significance level.

The frequency distributions in five categories of July–September (August–September) rainfall which have 20% chance when the entire data set is considered for favourable and unfavourable phases of ENSO and of the composite index of the ENSO index and EQWIN, derived by linear multiple regression analysis, for June (July), are shown in figures 4(b) and (c) (figures 5(b) and (c)) respectively. It is seen that the sign of ENSO has a large impact on the chance of occurrence of the lowest rainfall category in both the cases. It is interesting that the frequency of the highest July–September rainfall category is close to the climatological frequency of 20% for favourable as well as unfavourable ENSO index. Thus, ENSO appears to have very little impact on the frequency of the highest July–September rainfall category. On the other hand EQUINOO and hence the composite index has a substantial impact on the highest July–September rainfall category. Note that for both the cases, unfavourable (favourable) values of the composite index (of magnitude larger than 0.15), there is no chance of occurrence of the highest (lowest) rainfall categories. Thus the incorporation of EQWIN is seen to have had a substantial impact on the frequency distributions.

## 5. Discussion

We have addressed the problem of prediction of all-India rainfall during the whole and parts of the summer monsoon season, by focusing on ENSO and EQUINOO, which are considered to be the dominant modes determining the interannual variation of the ISMR. We have shown that the relationships of the all-India rainfall during June–September, July–September and August–September with simultaneous values of the ENSO and EQUINOO indices are strong. Hence we expect an accurate prediction of these indices to lead to prediction of the all-India rainfall for these periods with reasonable skill. While there has been phenomenal progress in prediction of ENSO with coupled models, prediction of EQUINOO is still a challenge. If the models were developed to a level at which the evolution of EQUINOO can also be predicted, then this association of the rainfall with the simultaneous values of the indices can be used to generate predictions of the all-India rainfall in these periods.

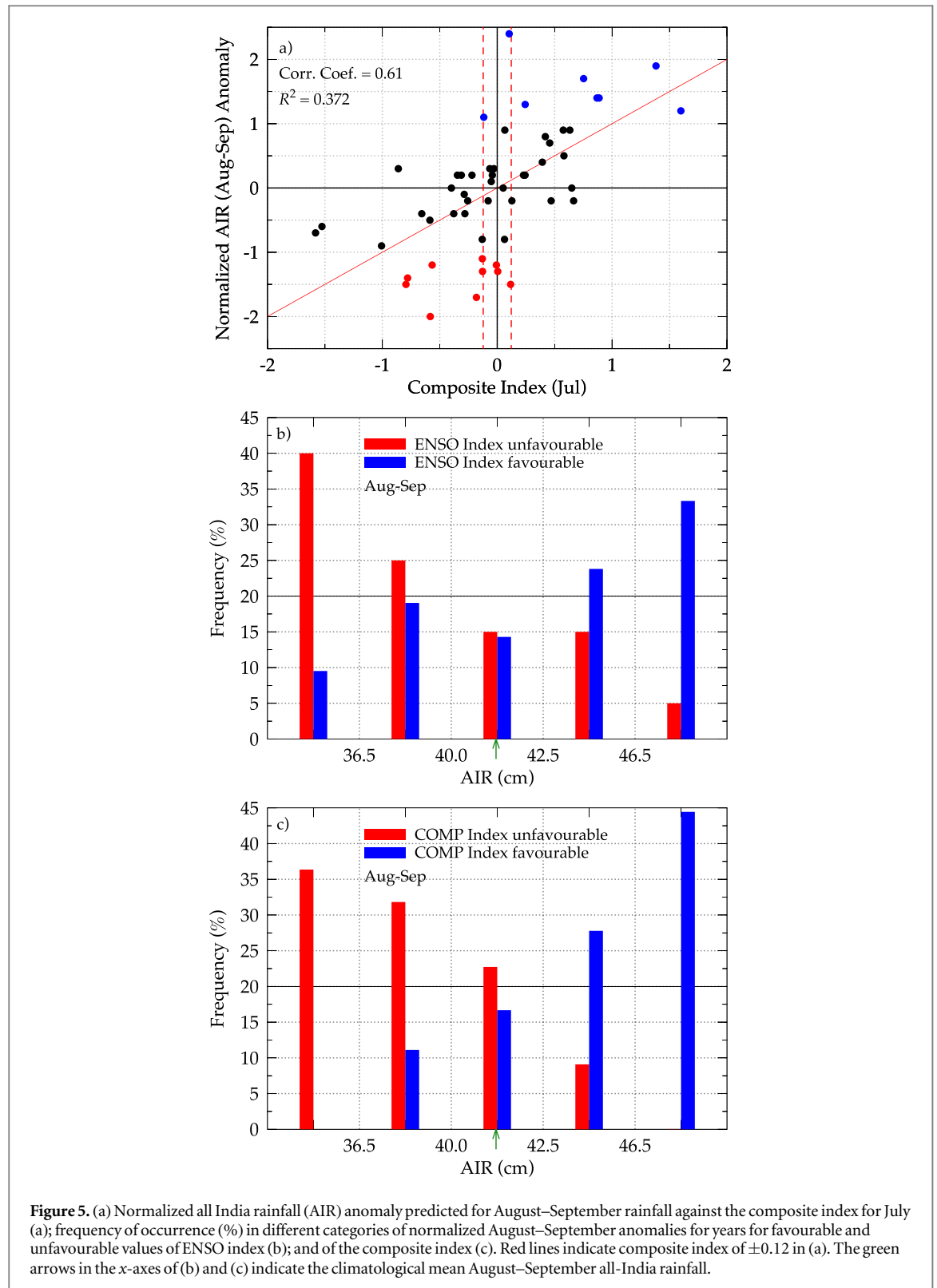
We have also shown that the all-India rainfall during July–September and August–September is well correlated with the values of ENSO and EQUINOO indices in the previous month and better correlated with a composite index for the previous month



**Figure 4.** (a) Normalized all India rainfall (AIR) anomaly predicted for July–September rainfall against the composite index for June (a); frequency of occurrence (%) in different categories of normalized July–September anomalies for years for favourable and unfavourable values of ENSO index (b); and of the composite index (c). Red lines indicate composite index of  $-0.27$  and  $0.12$  in (a). The green arrows in the x-axes of (b) and (c) indicate the climatological mean July–September all-India rainfall.

determined by bivariate analysis (0.49 and 0.61 respectively). It is interesting to compare our approach with the predictable mode approach proposed by Wang *et al* (2007), which has been extensively applied in the last few years (e.g. Lee *et al* 2011, Lee *et al* 2013, Wang *et al* 2014). We have shown that for the all-India rainfall during the summer monsoon season, July–September and August–September, ENSO and

EQUINOO together explain a large fraction of the total variability. The dynamical origins of these modes are understood rather well. Also, we have developed simple empirical models of prediction of the all-India rainfall from ENSO and EQUINOO states for one month prior to parts of the season which have reasonable skill for prediction of July–September and August–September rainfall. Thus all the criteria for



**Figure 5.** (a) Normalized all India rainfall (AIR) anomaly predicted for August–September rainfall against the composite index for July (a); frequency of occurrence (%) in different categories of normalized August–September anomalies for years for favourable and unfavourable values of ENSO index (b); and of the composite index (c). Red lines indicate composite index of  $\pm 0.12$  in (a). The green arrows in the x-axes of (b) and (c) indicate the climatological mean August–September all-India rainfall.

predictable modes appear to be satisfied. The major difference is that the dominant modes in the studies using the predictable mode approach are determined by EOF analysis of the observed variation of the variable to be predicted, and are thus specific to the problem addressed.

Clearly, adequate skill of prediction of ENSO and EQUINOO is essential for better predictions of the

Indian monsoon rainfall with our approach. The recent experience of the prediction of the El Niño during the summer monsoon seasons of 2012 and 2014 suggests that further improvement in the skill of prediction of ENSO would help. The major challenge is, however, improvement of the skill of prediction of EQUINOO by dynamical models. A deeper insight into the physics of triggering and evolution of the

**Table 4.** Contingency table for the relation between August–September rainfall with the July composite index. Vertical dashed lines in figure 5(a) indicate the thresholds of composite anomaly.

July composite index and August–September AIR	Normalized August–September rainfall < -1.0	August–September rainfall normal	Normalized August–September rainfall > 1.0
Composite anomaly < -0.12	7	15	0
Composite anomaly normal	3	8	2
Composite anomaly > 0.12	0	12	6

positive phase of EQUINOO could be gained by modelling studies of the different hypotheses proposed for triggering of the positive IOD events (Annamalai *et al* 2003, Francis *et al* 2007 and references therein), since the first step in triggering of such events is triggering of the positive EQUINOO phase. The simulation of the link between EQUINOO and the Indian monsoon rainfall could be improved by investigations of the processes suggested to be important such as the modulation of the interplay between the local Hadley circulation in the Indian longitudes and the Walker circulation associated with the El Niño events, such as that of 1997 (Slingo and Annamalai 2000) and the interaction between equatorial waves and physical processes which determines the rainfall anomalies over the eastern equatorial Indian Ocean and the Indian region (Annamalai 2010).

Whether the incorporation of information/prediction of EQUINOO and hence the composite indices derived here into the existing statistical models leads to improvement in skill also needs to be explored. The magnitude of the correlation coefficients of the predictors used in the statistical models developed by Rajeevan *et al* (2007) for prediction before the summer monsoon season and at the end of June (first and second stage forecasts) is in the range 0.36–0.55. The magnitudes of the correlation coefficient of the composite index for June with the July–September rainfall (0.49) is within the range of these predictors whereas that of the July composite index with August–September rainfall (0.61) is higher than that of the best-correlated predictor. It may be worthwhile to develop statistical models based on these indices for the second and later stage forecasts of the ISMR.

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