1. Introduction

Even though the interannual standard deviation of South Asian summer monsoon (SASM) accounts only for 10% of the total rainfall (Turner and Annamalai, 2012), these variations have significant impacts on agricultural production and water availability in this region. A part of the interannual variations is due to internal atmospheric variability and may thus limit the predictability of SASM (Sperber et al., 2001; Saha et al., 2011).

A large part of the predictability is believed to be related to forcing from the tropical oceans (Pacific, Indian, and Atlantic), and the fact that tropical oceans act as slowly varying boundary conditions on the atmosphere provides confidence in the potential predictability of SASM. El-Niño southern oscillation (ENSO) is probably the most important driver of SASM variability because of its global impacts through teleconnections (e.g. Trenberth et al., 1998; Alexander et al., 2002; Deser et al., 2004). However, the effect of ENSO on SASM has become weaker in the recent decades (Krishna et al., 1999; Yadav et al., 2009). Some studies have suggested that the Indian Ocean Dipole (IOD), which has also an influence on SASM (e.g. Pokhrel et al., 2012; Chaudhari et al., 2013; Cherchi and Navarra, 2013), has modified the ENSO teleconnection to SASM (Ashok et al., 2004; Ashok and Saji, 2007). Kucharski et al. (2007, 2008) linked the weakening of the ENSO–SASM relationship to the covariances of SSTs in the southern equatorial Atlantic with ENSO, which show an anticorrelation in the recent decades. The topical Atlantic influence on SASM is due to a Gill-type quadrupole response in streamfunction to a Atlantic positive (negative) heating that leads to high (low) pressure over the Arabian Sea and India thus induces low-level divergence (convergence) and reduced (increased) SASM precipitation (Kucharski et al., 2009; Wang et al., 2009).

Maximum covariance analysis (MCA; e.g. Bretherton et al., 1992; Newman and Sardeshmukh, 1995) is a robust tool to estimate coupled modes of variability. MCA has been recently applied to the SASM rainfall and SSTs (Mishra et al., 2012; referred to as M12 in the following). M12 found that the first mode was related to the ENSO influence on SASM rainfall and showed that an overall drying is related to El Nino-type SSTs in the eastern Pacific region. The second MCA rainfall mode identified by M12 showed a more complex pattern with increased rainfall in southern India and reduced rainfall in the northeastern parts. The coupled SST pattern is related to warming mainly in the eastern Indian Ocean and South China Sea, but also in the Arabian Sea and Bay of Bengal. M12 argued that such an SST pattern is related to the previous year ENSO. On the other hand, Rao et al. (2010) argued that such a pattern might be a representative of the IOD. Unlike the results of M12, some recent studies (e.g. Chaudhari et al., 2015) have pointed out that the second empirical orthogonal function (EOF) of precipitation is related to the IOD.

The purpose of this study is to interpret the MCA modes between SASM precipitation and tropical SSTs further, also taking into account the resent results of a possible tropical Atlantic influence on the SASM.

2. Data and methods

For precipitation, Asian precipitation – highly resolved observational data integration toward evaluation of
water resources (APHRODITE) is used (Yatagai et al., 2012) with horizontal resolution of 0.5° × 0.5°. Also, the global (1° × 1°) HadISST sea surface temperature (SST) data set (Rayner et al., 2003) is used. For the large-scale circulation (geopotential heights and winds) characteristics, the monthly mean reanalysis data of NCEP/NCAR (Kalnay et al., 1996) with horizontal resolution of 2.5° × 2.5° are used.

All analyses are performed on the seasonal mean JJAS (June to September) data from 1951 to 2007. The decadal signal is removed by subtracting an 11-year running mean. For the statistical significance of correlations, a Student’s t-test is used.

MCA is performed to identify coupled patterns between SASM precipitation and tropical SSTs. Some of the issues related to MCA analysis are discussed by Newman and Sardeshmukh (1995). They found that the analysis gives robust results for extracting coupled signals and has small systematic bias. In this study, we investigate the influence of SSTs on SASM precipitation, therefore we focus on the heterogeneous correlation maps. The correlation coefficients between the expansion coefficients (ECs) time series of the two fields for a particular mode are also calculated. The squared covariance fraction (SCF) indicates the percentage of covariance explained by the particular mode and is calculated following the study by Bretherton et al. (1992).

3. Results and discussions

Figure 1(a) shows the spatial structure of the mean JJAS precipitation over South Asia. The mean precipitation is above 10 mm day\(^{-1}\) over the Western Ghats and the adjoining areas of Bay of Bengal. Other maxima of rainfall can be seen over central India, where mean rainfall is between 6 and 10 mm day\(^{-1}\). The monsoon penetrates into northern Pakistan along the foothills of Himalayas but the mean rainfall remains below 6 mm day\(^{-1}\) over northern India and Pakistan.

3.1. SST-based indices in the tropical Oceans and their relationship with SASM precipitation

The NINO3.4 index is used to classify SST variability in the Pacific related to ENSO. It is defined as the average SST anomalies in the region 5°S–5°N and 170°E–120°W. Positive (negative) values of NIN03.4 index correspond to El-Niño (La-Nina) type conditions in the Pacific. The IOD index is defined as the SST anomalies difference between the tropical western Indian Ocean (5°S–70°E, 10°S–10°N) and the tropical southeastern Indian Ocean (90°E–110°E, 10°S–0°S) following the study by Saji et al. (1999). A positive IOD index characterizes warmer than normal water in the tropical western Indian Ocean and cooler than normal water in the tropical eastern Indian Ocean. Figure 1(b) and (e) shows the correlation between NINO3.4 and SASM precipitation and tropical SSTs, respectively. The SSTs in the Pacific show a typical ENSO pattern but the correlations also show significant positive (negative) values in the western (eastern) Indian Ocean which resembles the IOD pattern (Figure 1(f)). The correlation between NINO3.4 and IOD indices is 0.44 for the period considered which is significant at 95% level. The IOD index also shows significant correlation with SSTs in the Pacific (typical ENSO structure) (Figure 1(f)). However, the response of NINO3.4 and IOD is different in the SASM precipitation. NINO3.4 is negatively correlated with SASM precipitation over the whole region, whereas IOD is negatively correlated with the precipitation over Western Ghats and northeastern India and positively correlated with the precipitation over central India (e.g. Chaudhari et al., 2013). We have also assessed the sensitivity of the above results with respect to alternative ENSO and IOD definitions. The results turn out to be very similar if the NINO3 index is used instead of the NINO3.4 index. For IOD, we have tested the average negative SST in the eastern pole (90°E–110°E, 10°S–0°S), which has been used alternatively as IOD definition in, e.g. Rao et al., 2010, and may be viewed as the region where IOD develops first. We will refer to this index as IOD\(_{\text{east}}\) in the following. We have verified that the JJAS IOD\(_{\text{east}}\) index is highly correlated (0.75) with the canonical IOD index in its peak season (September to November) season. This result is consistent with the study of Krishnamurthy and Kirtman (2003). The results for the IOD\(_{\text{east}}\) correlation with rainfall over the SASM region are similar to that for the canonical IOD definition. However, the corresponding SST pattern (see Supporting Information) is dominated by the eastern Indian Ocean cooling and shows less covariability with eastern Pacific SST anomalies.

The south tropical Atlantic index (STAI) is an indicator of the SST anomalies in the Gulf of Guinea, the eastern tropical South Atlantic Ocean. It is calculated with SST anomalies in the region (30°W–10°E, 20°S–0°S) as suggested by Enfield et al., 1999. Positive values of STAI correspond to warmer than normal SSTs in the eastern tropical South Atlantic Ocean. The correlation of STAI with SASM precipitation shows a dipole structure with negative correlations over central India and north western parts of South Asia. STAI does not show any significant correlations with tropical Indian and Pacific SSTs, indicating that the variability in the south tropical Atlantic is independent of ENSO.

All correlations calculated in Figure 1 are contemporaneous for seasonal JJAS means. This assumption has been shown to be valid using lead-lag correlations between an Indian monsoon rainfall index and ENSO as well as STAI in the study by Kucharski et al., 2007 and Kucharski et al., 2008. Also for the IOD influence, this assumption is typically made (e.g. Rao et al., 2010).
3.2. Coupled patterns of SASM precipitation variability in the global tropics

We first consider the leading patterns of SASM precipitation variability and their relationship with global tropical SSTs. Figure 2 shows the leading three modes of MCA heterogeneous correlation maps, between global tropical SSTs and precipitation over South Asia. The correlations between the EC of global tropical SSTs and SASM precipitation for the first, second and third mode of MCA are 0.65, 0.61 and 0.63, respectively, with SCF of 64.3, 12.1 and 9.8%, respectively, and are well separated from the following modes (which have SCF of about 2%). As expected, ENSO is
Figure 2. Coupled patterns of SASM precipitation and global tropical (0°–360°E, 20°S–20°N) SST variability based on MCA for 57 years (1951–2007). The patterns indicated by color shading are heterogeneous correlation coefficients for leading three modes between (a)–(c) SST expansion coefficient time series and precipitation (d)–(f) precipitation expansion coefficient time series and SST. The SFC and temporal correlation (r) between the SAM and SST expansion coefficients are indicated at the top in (d)–(f).

The leading mode of variability in the tropics coupled with SASM precipitation, which explains the largest covariance. EC of global tropical SSTs first mode has a correlation of 0.97 with NINO3.4 index. The corresponding negative anomalies in SASM precipitation (Figure 2(a)) is in agreement with previous studies, i.e. SASM precipitation tends to be generally suppressed during El-Niño years. This result is also in agreement with the study of Mishra et al. (2012).

The second mode of MCA shows that the above normal SSTs over tropical Atlantic, Arabian Sea, the Bay of Bengal and the South China Sea (Figure 2(e)) are coupled with below normal rainfall in central India and above normal rainfall over southern India to the east of the Western Ghats (Figure 2(b)). The EC of global tropical SSTs second mode is correlated with the IOD_east index (−0.45). M12 have found a similar second mode and have linked this mode to the previous year’s ENSO indexes.

The third mode for global tropical SSTs has spatial patterns in SASM precipitation and Atlantic SSTs (Figure 2(c) and (f)) similar to STAI correlation patterns (Figure 1(d) and (g)). The correlation of the SST EC and STAI is 0.46. This clearly shows that the third mode of variability in the SASM precipitation is related to Atlantic SSTs. Interestingly, the second mode is also correlated with the STAI (correlation = 0.5). If one combines SST modes 2 and 3 as STAI\_rec = a EC2 + b EC3, where a and b are the correlations of EC2 and EC3 with STAI, respectively, then this reconstructed STAI\_rec has a correlation of 0.77 with STAI (see Supporting Information). The correlation of STAI\_rec with SASM rainfall and with SSTs indeed confirms the similarity...
Coupled modes of South Asian monsoon variability in the tropics

Figure 3. Coupled patterns of SASM precipitation (60°–100°E, 5°–35°N) and tropical Atlantic (60°W–15°E, 20°S–20°N) SST variability based on MCA on 57 years (1951–2007). The patterns indicated by color shading are heterogeneous correlation coefficients for leading mode between (a) SST expansion coefficient time series and SASM precipitation (b) vice versa. The SFC and temporal correlation \( r \) between the South Asian monsoon and SST expansion coefficients are indicated at the top in (b). The rectangle shows the MCA domain in Atlantic.

with the STAI SST pattern and influence on SASM rainfall (see Supporting Information and Figure 1(c) and (f)). This demonstrates that the STAI influence is mainly distributed in modes 2 and 3 of the global MCA. The discovery that the Atlantic is contributing to the statistically coupled modes of variability leads us to the further investigation discussed in the next section.

To further understand the second mode in the above MCA and the role of IOD in the SASM interannual variability, we repeated the analysis by taking SSTs only over tropical Indian Ocean (30°–120°E and 20°S–20°N) and SASM precipitation. The leading mode in this case looks similar to the second mode obtained in the global tropical SST pattern (Figure 2(e)), and it accounts for 43.7% of the SFC in this regional domain with high correlation between ECs of SST and SASM precipitation. Although the study of Mishra et al. (2012) linked a similar mode to the previous winter ENSO, the rainfall pattern over the SASM region resembles that of the (negative) IOD (see Figure 1(c)), and the SST pattern resemble that of the (negative) eastern IOD pole (see Supporting Information). The correlation between negative SST EC1 and IOD_{east} is 0.8. The second mode shows a dipole structure in rainfall over the SASM region and a cooling in the southern Indian region. However, there are also anomalies in the Atlantic region that resemble the STAI pattern (see Figure 1(g)). Also, the rainfall pattern of the second mode resembles the STAI influence (Figure 1(d)). It is therefore likely that this second regional Indian Ocean mode is strongly influenced by forcings from the Atlantic region.

The third mode in this regional MCA with SFC 13.8% has weak anomalies in the Indian Ocean region but shows large negative values in the eastern Pacific region that resemble that of ENSO. Also, the rainfall mode in the SASM region shows overall positive values that are consistent with the (negative) ENSO influence.

3.3. SASM coupled mode of variability in the tropical Atlantic

The regional MCA over tropical Atlantic and SASM precipitation (Figure 3(a) and (b)) shows that the variability in the SST anomalies in the Gulf of Guinea is the leading mode in the tropical Atlantic coupled with SASM precipitation. The SFC is 59.9% and the correlation of SST EC with STAI is 0.98. This mode is well separated from the second mode (SFC = 22.7%). The spatial patterns of precipitation (Figure 3(a)) over South Asia are also very similar to the reference correlation map of STAI (Figure 1(d)). For consistency with the STAI correlation maps (Figure 1(d) and (g)), the EC time series of both SST and precipitation were multiplied with −1 before plotting the heterogeneous correlation maps shown in Figure 3.

Spatial patterns obtained by regressing the seasonally averaged 850 hPa geopotential heights (m) and winds (m s\(^{-1}\)) on to the standardized EC (leading mode) of the precipitation shows significant positive geopotential anomalies and the related anticyclonic circulation

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over the Arabian Sea, which cause decreased precipitation over central India and the northwestern parts of South Asia related to positive SST anomalies over the tropical Atlantic. The negative geopotential anomalies and related circulation can be linked with increased precipitation over Bangladesh and northeastern India. We have tested the above results using different reanalysis produces and found that the main features are robust. As outlined in the Section 1, the physical mechanism for the tropical Atlantic influence on the SASM region relies on a Gill-type response to the SST-induced heating anomaly. The response to a positive heating anomaly is a large-scale quadrupole in stream function and vorticity (Kucharski et al., 2009). One center of this response is located over the Arabian Sea/Indian region with a low-level negative vorticity anomaly, leading to low-level divergence and reduced rainfall over the large parts of west and central India. Also, the Somali jet is weakened as part of this response. This response is further reinforced as the surface pressure adjusts to the decreased heating local (rainfall), resulting in a high-pressure anomaly over western-central India, as shown in Figure 4. The opposite response over the northeastern parts of the SASM region could be related to a compensating convergence induced by the divergence over central-western India.

As a new result, we have shown that Atlantic Ocean SST variability is contributing to MCA modes 2 and 3 of global tropical SST with SASM. The south tropical Atlantic appears as the well-separated leading mode of tropical Atlantic SST with SASM precipitation. Increased (decreased) precipitation over the Western Ghats, central India and the northwestern parts and decreased (increased) precipitation over the northeastern parts of South Asia are related to negative (positive) SST anomalies over the tropical South Atlantic in this coupled mode. The influence of negative (positive) tropical South Atlantic SSTs on the SASM region can be explained as Gill-type response that induces cyclonic (anticyclonic) circulation anomalies over the Arabian Sea and central-western Indian region. This mode is also associated with increased (decreased) pressure and thus decreased (increased) precipitation over Bangladesh and adjoining areas.

This study shows that predicting SST variability in the tropical Atlantic region may provide a crucial contribution to SASM predictability. This is particularly of interest because the tropical Atlantic continues to be a region with severe model biases (Richter et al., 2014).

4. Conclusions

We have shown that ENSO is the leading mode with explained covariance 64.3% of a MCA performed between tropical SSTs and SASM precipitation, whereas eastern pole of the IOD contributed to the second global mode and is the leading mode when the MCA is performed regionally between Indian Ocean SSTs and SASM. This is consistent with previous findings.

As a new result, we have shown that Atlantic Ocean SST variability is contributing to MCA modes 2 and 3 of global tropical SST with SASM. The south tropical Atlantic appears as the well-separated leading mode of tropical Atlantic SST with SASM precipitation. Increased (decreased) precipitation over the Western Ghats, central India and the northwestern parts and decreased (increased) precipitation over the northeastern parts of South Asia are related to negative (positive) SST anomalies over the tropical South Atlantic in this coupled mode. The influence of negative (positive) tropical South Atlantic SSTs on the SASM region can be explained as Gill-type response that induces cyclonic (anticyclonic) circulation anomalies over the Arabian Sea and central-western Indian region. This mode is also associated with increased (decreased) pressure and thus decreased (increased) precipitation over Bangladesh and adjoining areas.

This study shows that predicting SST variability in the tropical Atlantic region may provide a crucial contribution to SASM predictability. This is particularly of interest because the tropical Atlantic continues to be a region with severe model biases (Richter et al., 2014).

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Supporting information

The following supporting information is available:

Figure S1. Correlation coefficients between an eastern IOD pole index (negative average SST anomalies in the region 90°–110°E,
10°–0°S; referred to as IOD$_{segd}$ the main text) and (a) SASM precipitation (b) SST. Black contours show the correlation values at 95% significance.

**Figure S2.** Coupled patterns of SASM precipitation and tropical Indian Ocean (30°–120°E and 20°S–20°N) SST variability based on MCA for 57 years (1951–2007). The patterns indicated by color shading are heterogeneous correlation coefficients for leading three modes between (a)–(c) SST expansion coefficient time series and precipitation; (d)–(f) precipitation expansion coefficient time series and SST. The SFC and temporal correlation (r) between the SAM and SST expansion coefficients are indicated at the top in (d)–(f).

**Figure S3.** Correlation of the reconstructed south tropical Atlantic index, STAI$_{rec}$ (see main text, Section 3.2 for definition) (a) with SAESM rainfall and (b) with SSTs.

**Figure S4.** Time series (1951–2007), STAI (Black), EC2 (Green), EC3 (Blue) and STAI$_{rec}$ (Red). EC2, EC3 and STAI$_{rec}$ are normalized by 100.

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