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Sensitivity of precipitation to sea surface temperature over the tropical summer monsoon region—and its quantification

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Abstract Over the tropical oceans, higher sea surface temperatures (SST, above 26 °C) in summer are generally accompanied by increased precipitation. However, it has been argued for the last three decades that, any monotonic increase in precipitation with respect to SST is limited to an upper threshold of 28–29.5 °C, and beyond this, the relationship fails. Based on this assessment it has often been presumed that, since the mean SSTs over the Asian monsoon basins (Indian Ocean and north-west Pacific) are mostly above the threshold, SST does not play an active role on the summer monsoon variability. It also implies that increasing SSTs due to a changing climate need not result in increasing monsoon precipitation. The current study shows that the response of precipitation to SST has a time lag, that too with a spatial variability over the monsoon basins. Taking this lag into account, the results here show that enhanced convection occurs even up to the SST maxima of 31 °C averaged over these basins, challenging any claim of an upper threshold for the SST-convection variability. The study provides us with a novel method to quantify the SST-precipitation relationship. The rate of increase is similar across the basins, with precipitation increasing at ~ 2 mm day^{-1} for an increase of 1 °C in SST. This means that even the high SSTs over the monsoon basins do play an active role on the monsoon variability, challenging previous assumptions. Since the response of precipitation to SST variability is visible in a few days, it would also imply that including realistic ocean–atmosphere coupling is crucial even for short term monsoon weather forecasts. Though recent studies suggest a weakening of the monsoon circulation over the last few decades, results here suggest an increased precipitation over the tropical monsoon regions, in a global warming environment with increased SSTs. Thus the signature of SST is found to be significant for the Asian summer monsoon, in a quantifiable manner, seamlessly through all the timescales—from short-term intraseasonal to long-term climate scales.

Keywords Ocean atmosphere interaction · Asian monsoon · SST precipitation relationship · Climate change

1 Introduction

The sea surface temperatures (SST) over the tropical oceans stay mostly above 26 °C during summer, with values reaching up to 31 °C over the warm pool regions (Fig. 1a). These high SSTs persist throughout the season, and at the same time show variability on intraseasonal timescales, with a change of up to 1–2 °C within a week or two. SST can be considered as the single representative quantity of the ocean, which communicates the ocean's thermal inertia to the atmosphere, through an exchange of the surface fluxes (Deser et al. 2010). The atmosphere responds back, as high SSTs over the tropics are generally accompanied by increased precipitation (Trenberth and Shea 2005; Vecchi and Harrison 2002) (Fig. 1b). It is apparently straightforward to assume that such a relationship holds for the whole range of possible SSTs (26–31 °C), throughout the monsoon basins, during the

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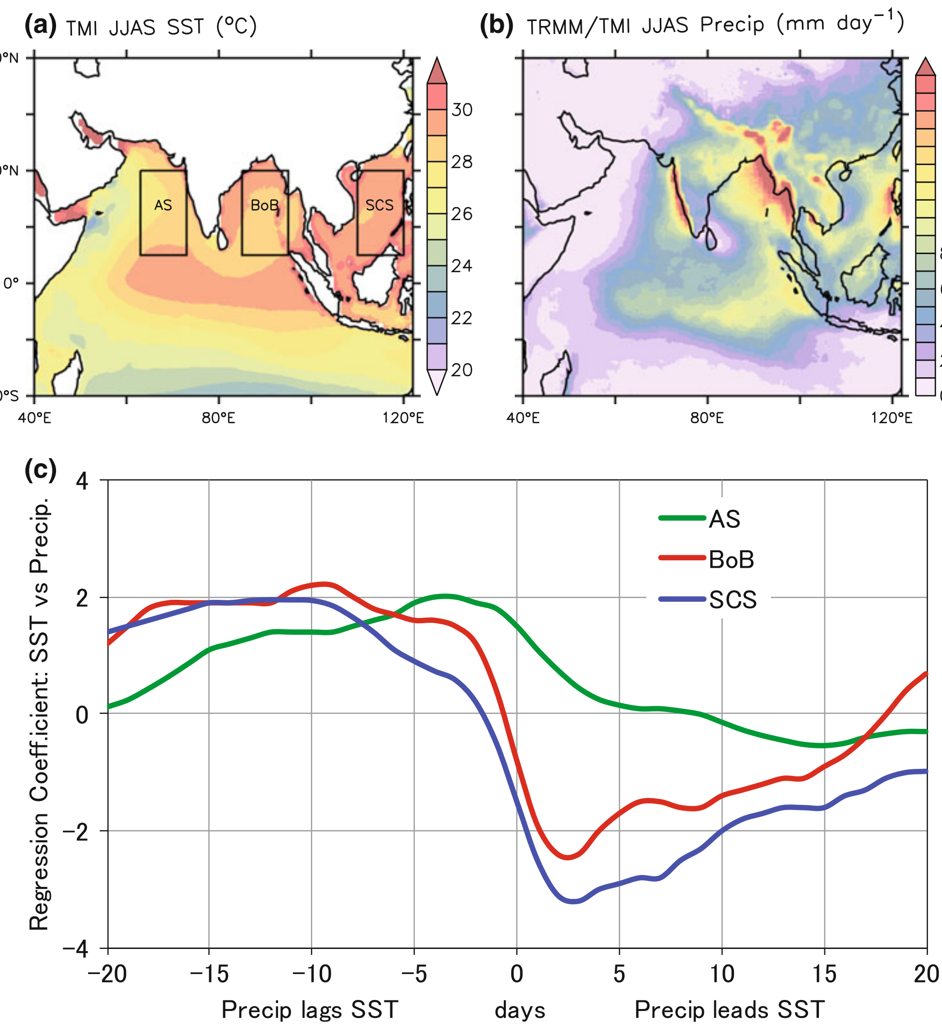

Fig. 1 Climatology of (**a**) SST (colors; °C) and (**b**) precipitation (colors; mm day^{-1}) over the Asian monsoon region, during June–September, based on observations (years 1998–2011). Shading conventions are represented at the side of the figures. (**c**) Observed daily lead/lags are represented by the regression coefficients of change in precipitation in units of mm day^{-1} per °C of SST. SST and precipitation are averaged over the inset rectangles in (**a**); Arabian Sea (AS, 63–73°E), Bay of Bengal (BoB, 85–95°E) and the South China Sea (SCS, 110–120°E) over similar latitudes (5–20°N). A positive regression coefficient when precipitation lags the SST indicates that the SST is driving the atmosphere. Similarly, a negative coefficient when precipitation leads the SST indicates that the atmosphere is driving the SST. The magnitude of the regression coefficient refers to the intensity of the driving force, and the lag/lead days corresponding to maximum values of the coefficient denotes how quickly the atmosphere responds to SST and vice versa. Significance of the maxima of regression coefficients were assessed to be greater than 95 % level by means of a two-tailed Student's test

boreal summer (June–September) (Sobel 2007). However, the non-linear response between the two variables makes it difficult to assess the relationship. It has been argued for the last three decades that, any monotonic increase in precipitation with respect to SST is limited to an upper threshold of 28–29.5 °C, and beyond this, the relationship fails (e.g., Gadgil et al. 1984; Graham and Barnett 1987; Waliser et al. 1993; Zhang 1993; Meenu et al. 2012; Rajendran et al. 2012; Sabin et al. 2012). Based on this assessment, it has often been presumed that, since the mean SSTs over the monsoon basins viz. the Arabian Sea, Bay of Bengal and the South China Sea are mostly above the threshold (Fig. 1a), SST is a slave over the region and does not play an active role on the summer monsoon variability (Gadgil et al. 1984; Graham and Barnett 1987).

Though ocean–atmosphere coupled models are used for seasonal monsoon forecasts, almost all of the leading operational forecasters use stand-alone atmospheric models forced with observed SSTs for the short term weather forecasts. Other than practical issues (initialization, operational expenses etc.), a major reason might be that the persistence of mean SST is considered more significant than a continuous evolution of SST and its effects on convection. A reconsideration of the role of ocean is crucial especially at the moment when a $1 billion National Monsoon Mission (Stone 2012) has been setup by the

Government of India to improve the short and long term monsoon forecasts—for a large population whose socio-economic activities depend on the vagaries of the monsoon. It is also significant in a changing climate, as the tropical SSTs rise in response to the greenhouse warming. In the current study, the SST-precipitation relationship over the Asian monsoon region is re-examined using recent high quality satellite data and simulations from a state of the art coupled model. Instead of using monthly data, daily data with appropriate lead-lags for each basin, are utilized to get a new perspective on the co-variability between SST and precipitation. This is based on the realization that the SST-precipitation relationship has a lag of several days, that too with a spatial variability, over the Arabian Sea, Bay of Bengal and the South China Sea (Wu et al. 2008; Roxy et al. 2012).

It is fairly understood that a transitional SST range of 25.5–27.5 °C is conducive for deep convection (Gadgil et al. 1984; Graham and Barnett 1987; Lau et al. 1997; Johnson and Xie 2010). Various studies show that the frequency of occurrence of tropical convection increases significantly for an SST range of ~26–28 °C. However, it is not clear if such a monotonic increase of precipitation with SST can be maintained beyond this range. Is there an upper threshold for the SST-convection relationship during the Asian summer monsoon, and does it have any significance on the monsoon variability? There is large uncertainty and debate on the sensitivity of tropical precipitation with respect to SST over the tropical monsoon regions viz. Arabian Sea, Bay of Bengal and the South China Sea (Gadgil et al. 1984; Lau et al. 1997). The uncertainty lies in how linear the relationship is, and the factors contributing to the observed linearity/nonlinearity. Using monthly data, several studies on the Asian summer monsoon suggest that deep convection attain its peak values at SST ~28.5–29.5 °C and decreases with further increase in SST (Gadgil et al. 1984; Waliser et al. 1993; Bhat et al. 1996; Rajendran et al. 2012; Sabin et al. 2012; Meenu et al. 2012), propounding the nonlinearity in the SST-precipitation relationship. These studies portray an upper threshold over the Indian Ocean, especially over the Arabian Sea, with precipitation peaking up to SSTs of 29 °C and dipping beyond these values (Gadgil et al. 1984; Waliser et al. 1993; Rajendran et al. 2012; Meenu et al. 2012). For the Bay of Bengal, South China Sea and the north western Pacific, the relationship shown is mostly negative, as the mean temperatures here are generally above 29 °C (Loschnigg and Webster 2000; Wang et al. 2005; Rajendran et al. 2012). Based on these studies, it has been argued for several decades that, since the mean SSTs over the monsoon basins are mostly above this threshold (Fig. 1a), local SST is not a determining factor for the variability in precipitation over these regions (Gadgil et al. 1984).

Several explanations have been attributed to the upper threshold and negative SST-precipitation relationship over the monsoon basins. A set of studies suggest that along with positive SST anomalies, the convective available potential energy (CAPE) should also be positive for enhanced convective activity. These studies point out that the available energy is used up as the convection builds up, making it impossible to sustain any further convective activity, thereby resulting in a breakdown of the relationship (Gadgil et al. 1984; Bhat et al. 1996). Another set of studies show that any apparent decrease in precipitation with respect to SST is more likely to be influenced by large-scale subsidence forced by nearby or remotely generated deep convection (Lau et al. 1997; Su et al. 2003). Nevertheless, there is no consensus between these studies, and it is not clearly understood if defining an upper threshold for the SST-precipitation relationship is meaningful, especially for the tropical monsoon region, where the mean SSTs are mostly above 28.5 °C throughout the summer monsoon period. Further studies have suggested that the relationship is relative to the tropical-mean SSTs, and that convection occurs where the local SST exceeds those tropical-mean values, in a way that is consistent with moist static adjustment (Sobel 2007; Johnson and Xie 2010). This might explain why the minimum threshold for convection varies for different locations, but does not explain if convection occurs beyond an upper threshold. In fact, a recent study (Johnson and Xie 2010) using an ensemble of coupled models indicated an existence of an upper threshold—during both present day and future simulations—even when the SSTs are considered with respect to the tropical-mean values.

There are some fundamental shortages in the analysis of SST-precipitation in the studies cited above.

First, the SSTs and corresponding convective variables (e.g., precipitation, outgoing longwave radiation) utilized are on a monthly timescale; and the relationship demonstrated is without examining the lag/leads. In reality, nature does not go by a sequence of calendar month means. Figure 1c shows the lead lag relationship between SST and precipitation from observed fields. It is observed that the implied influence of SST on precipitation over the tropical monsoon region is not instantaneous (regression coefficients are near zero or low on the same day), but with a lag of several days or even weeks (when the positive regression coefficients are maximum). Even those few studies utilizing daily data, have looked into the relationship without considering the lag between these two fields (Sabin et al. 2012). A few studies which examined the time-lag relationship between SST and precipitation, however, deals with the role of the persistence of SST on monthly time scales (Wu and Kirtman 2005). It is also worth to note that, since precipitation acts as a limiting factor on the SST

(Waliser 1996), a simultaneous correlation between these variables almost always provides the SST influence on precipitation and vice versa too, making it difficult to single out the effect of one on the other. Hence, utilizing daily data which can represent the lag/leads would be more meaningful while examining the relationship between SST and convection.

Second, the SST-precipitation lag relationship has a spatial variability (Wu et al. 2008; Roxy et al. 2012). The response is fast over the Arabian Sea, with SST leading precipitation by $\sim$3–6 days, whereas it is slow over the Bay of Bengal and South China Sea, where SSTs lead precipitation by $\sim$10–13 days (Fig. 1c). It may seem that the observed time lag is a consequence of the northward propagation of convective bands over the monsoon basins (Jiang et al. 2004; Chou and Hsueh 2010). However, time-latitude plots of SST and precipitation anomalies show that the lag is consistent throughout the northward propagating latitudes, from the equator to 25°N (Roxy et al. 2012). Recent studies have shown that, the lagged response of convective activity to the underlying SST anomalies depends on the mean surface convergence and uplift over the region. The relatively stronger surface convergence over the Arabian Sea accelerates the uplift of the moist air resulting in a relatively faster response in the local precipitation anomalies (Roxy et al. 2012). Meanwhile, the response in the precipitation anomalies is relatively slower over the Bay of Bengal and South China Sea as these basins have a comparatively weaker surface convergence. Most of the earlier studies which examined the SST-convection relationship consider large domains, for example, the whole Indian Ocean. When considering the summer monsoon, the intra seasonal variability (ISV) over the different basins like the Arabian Sea, Bay of Bengal and South China Sea are out of phase (Sengupta et al. 2001; Xie et al. 2007), and a combination might distort the real picture, especially with monthly data. For example, when a correlation between monthly SST and precipitation over the whole tropical Indian Ocean is examined, the SSTs in the Arabian Sea might be having a 5 day lag relationship with precipitation at a particular phase of the ISV, and SSTs in the Bay of Bengal might be having a 12 day lag relationship with precipitation at a different phase of the ISV. The arguments here point out that the basins exhibiting different phases of ocean–atmosphere interaction and ISV should be considered separately for examining the atmospheric response to oceanic heating.

As hypothesized in a review by Sobel (2007), in an ideal one-dimensional model at a non-precipitating state, the rate of precipitation is a function of moist static energy, which in turn is a function of SST, and hence the precipitation rate should depend on SST only. Also, recent studies have shown that increased SSTs tend to increase the equivalent potential temperature (θ_e, analogous to moist static energy) over the surface, thereby destabilizing the lower atmospheric column, a condition favorable for enhancing the convection (Roxy and Tanimoto 2007, 2012; Wu 2010). Though a straightforward relationship between SST and convection has been implied in a one-dimensional model at non-precipitating state (Sobel 2007), there have been no observational studies to prove whether this happens in a precipitating state in nature (space–time dimensions). Besides, the earlier observations over the tropical monsoon regions do not attest to this argument. These 'apparently obvious but conflicting results' are one of the motivations to re-examine the relationship between SST and convection.

The current study examines the sensitivity of precipitation to SST by analyzing each monsoon basin separately, viz. the Arabian Sea (63–73°E), Bay of Bengal (85–95°E) and the South China Sea (110–120°E) over similar latitudes (5–20°N), and takes into consideration the spatial variability in the lead-lag between the two variables. The domains utilized in the current study are those regions were the large scale monsoon circulation is similar, and the surface fluxes dominate the evolution of SST, rather than processes such as the coastal dynamics, entrainment and advection (Vialard et al. 2011). Since the current study examines local SST-precipitation relationship, and since precipitation can also occur non-locally over the nearby ascending parts of the atmospheric circulation, a grid-by-grid examination is avoided (Lau et al. 1997). Instead, mean values averaged over large domains over specific monsoon basins are considered so that the effects of nearby ascending (or descending) cells of circulation are also factored in.

2 Data, analysis and methodology

2.1 Observed data

Examining and validating the SST-precipitation relationship requires high quality datasets with high resolution both in the temporal and spatial domains. Hence a suite of new high resolution satellite observations of SST and precipitation, and objective analysis of latent heat and shortwave fluxes, which are available since the last decade, are utilized in the present study. Daily SST and precipitation based on the TRMM Microwave Imager (TMI) on a $\sim$0.25° grid are used (Wentz et al. 2000). The satellite and observed fields are supplemented with daily air temperature, specific humidity and divergence fields at 1.5° grid based on the European centre for medium range weather forecasts (ECMWF) Interim (ERA-Interim) reanalysis (Dee et al. 2011). Considering the availability of all these variables across the recent years, data from 1998 to 2011 (14 years) are used in the present study.

2.2 Model simulations

The Climate Forecast System (CFSv2) is a fully coupled ocean–land–atmosphere-sea ice model from the National Centre for Environment Prediction (NCEP), with significant improvements since its first version (CFSv1) (Saha et al. 2010). This version of the CFSv2 is similar to the version of the NCEP model used for the climate forecast system reanalysis (CFSR) (Saha et al. 2010). The atmospheric component of the CFSv2 is the NCEP Global Forecast System (GFS) model. It adopts a spectral triangular truncation of 126 waves (T126) in the horizontal ($\sim 0.9°$ grid) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. The convection scheme employed in GFS is the Simplified Arakawa-Schubert (SAS) convection, with cumulus momentum mixing and orographic gravity wave drag (Saha et al. 2010). The ocean component is the modular ocean model version 4p0d (MOM4p0d) (Griffies et al. 2004), from the geophysical fluid dynamics laboratory (GFDL), which is a finite difference version of the ocean primitive equations configured under the Boussinesq and hydrostatic approximations. The zonal resolution is 0.5° and the meridional resolution is 0.25° between 10°S and 10°N, becoming gradually coarser through the tropics, up to 0.5° poleward of 30°S and 30°N. There are 40 layers in the vertical with 27 layers in the upper 400 m, with a bottom depth of approximately 4.5 km. The vertical resolution is 10 m from the surface to the 240 m depth, gradually increasing to about 511 m in the bottom layer.

The atmosphere, ocean, land and sea ice exchange quantities such as the heat and momentum fluxes every half an hour, with no flux adjustment or correction. The CFSv2 model is time integrated over a period of 100 years, and the simulated daily data for the last 60 years is used in the present study for the current analysis. In the model simulations with present day conditions ($1 \times CO_2$), the mixing ratios of time varying forcing agents such as atmospheric CO_2 ($\sim$398 ppm), CH_4, N_2O, etc. are set for the current decade, so that the model climate is comparable with the observed climate obtained from the recent high resolution data. Validation studies show that the features of the Asian summer monsoon, including its intraseasonal variability, are well simulated in the $1 \times CO_2$ model simulations (Roxy et al. 2012). For the $2 \times CO_2$ simulations, the CO_2 concentration of the model was gradually increased at a constant linear rate of 1 % year^{-1} up to double the levels, and then kept constant. The last 20 years of $1 \times CO_2$ and $2 \times CO_2$ simulations are utilized to examine the difference, and bring out the implications for a warming environment.

2.3 Methodology

The equivalent potential temperature (θ_e) of an air parcel increases with increasing temperature and moisture content. The vertical profile of θ_e may be used as a measure of vertical stability of the lower atmospheric column (Roxy and Tanimoto 2007). As an illustration, a decrease in θ_e with altitude may lead to unstable atmospheric conditions, which can increase the local convection. Similarly, an increase in near surface θ_e may suppress the convective activity over the region. The lower tropospheric air temperature and specific humidity from ERA interim reanalysis are used to derive the equivalent potential temperature (θ_e). In the present analysis, the equivalent potential temperature at 1,000 hPa (θ_{e1000}) is utilized instead of the vertical profile of θ_e, as it clearly demarcates the role of SST in influencing the lower atmospheric stability. The upper atmospheric (200 hPa) divergence is utilized for typifying the relative role of large scale circulation on convection.

To examine the lead/lag relationship between SST and precipitation, regressed precipitation is plotted against SST at different lead/lags. A positive regression coefficient observed when precipitation lags the SST indicates that the SST is driving the atmosphere. Similarly, a negative coefficient when precipitation leads the SST indicates that the atmosphere is driving the SST. The lag/lead time corresponding to the maximum values of the coefficient denotes how quickly the atmosphere responds to the SST anomalies and vice versa. Significance of the results were assessed by means of two-tailed student's t test whenever appropriate.

The domain under consideration are the open basins over similar latitudes (5–20°N, Fig. 1a), where the large scale monsoon circulation is active and the surface fluxes dominate the evolution of SST. Regions with strong coastal dynamical processes (Vialard et al. 2011), entrainment, advection and river runoff are excluded, for a better comparative analysis of the results across the domains.

3 Results

3.1 SST-precipitation relationship over the Asian monsoon basins

Figure 2a portrays the classical SST-precipitation relationship, from the observed variation of precipitation with SST "on the same day" (Gadgil et al. 1984; Waliser et al. 1993; Loschnigg and Webster 2000; Wang et al. 2008; Rajendran et al. 2012; Sabin et al. 2012; Meenu et al. 2012). For Arabian Sea, though the precipitation increases with increasing SST, it drops down once the SST goes

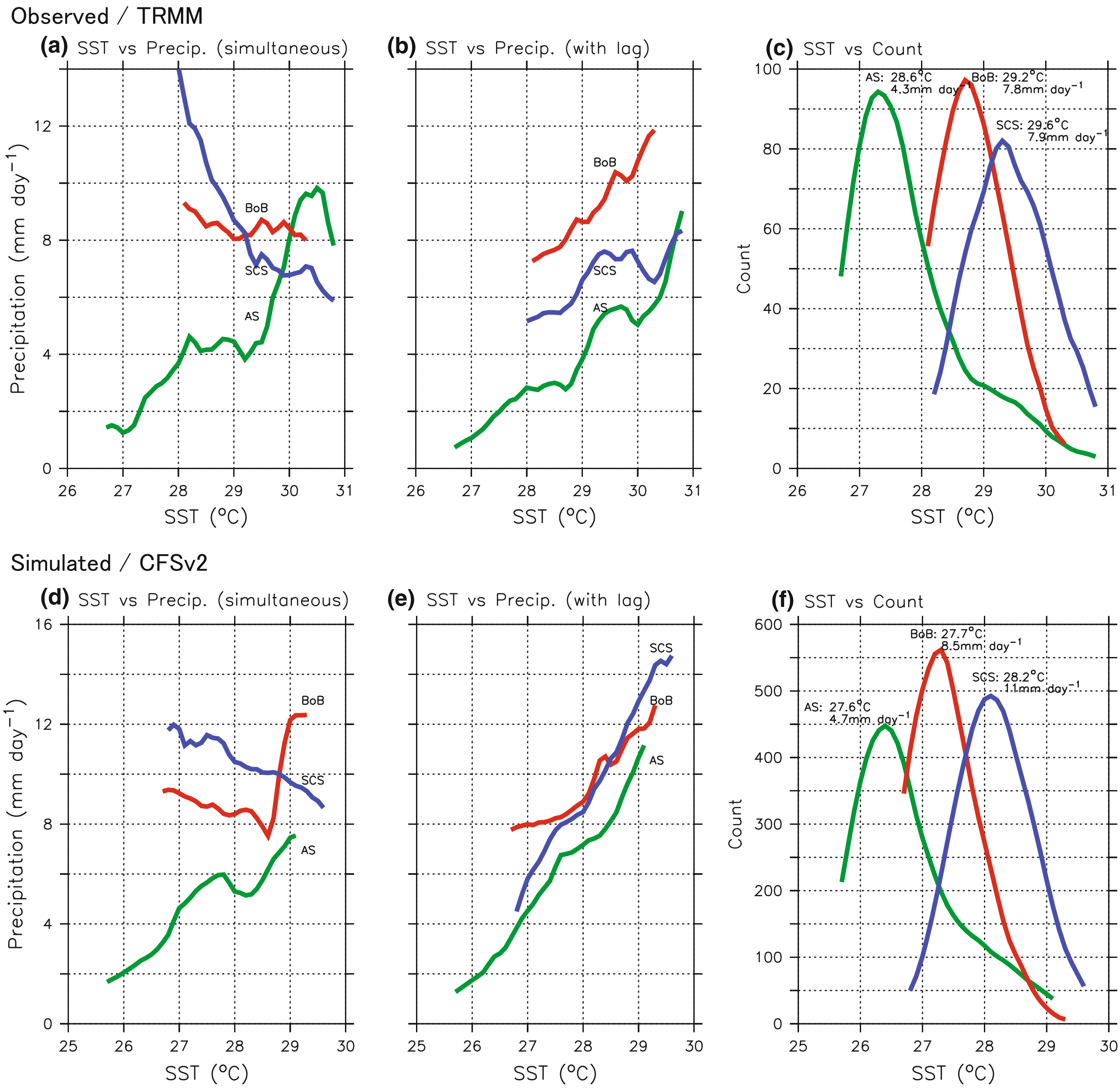

Fig. 2 Observed variation of precipitation (mm day^{-1}) with SST (°C) **a** simultaneously and **b** at observed lags over the Arabian Sea (AS, *green curve*), Bay of Bengal (BoB, *red curve*) and the South China Sea (SCS, *blue curve*), for June–September, during 1998 to 2011. **c** Number of times the average SST over the region is within the 0.1 °C SST bin. Model simulated results for **d** simultaneous and **e** lagged co-variability, along with the (**f**) count is given in the bottom panel. Values of mean SST and precipitation are noted for each region. The lags at maximum regression coefficient are 5, 10 and 12 days in observations, and 7, 12 and 11 days in model simulations, for AS, BoB and SCS, respectively

beyond an upper threshold of about 30 °C (29.5 °C using monthly data), as shown by previous studies (Gadgil et al. 1984; Sabin et al. 2012). For Bay of Bengal and South China Sea, the relationship is again similar to those depicted by earlier studies, with a negative correlation (Wang et al. 2005; Rajendran et al. 2012). The perception of the relationship completely changes when the inherent lag is considered for examining the co-variability between both the fields, as illustrated by Fig. 2b. This is because the impact of SST on the precipitation is not an instantaneous one, but at a lag, with the strength of the local surface convergence and uplift as one deciding factor in the response time (Roxy et al. 2012). Over the Arabian Sea, Bay of Bengal and the South China Sea, precipitation is found to exhibit an increase along with SST, in comparison with the co-variability shown in Fig. 2a. The rate of increase is similar across the basins, and quantifiable, with approximately 2 mm day^{-1} increase in precipitation for a 1 °C increase in SST. The results are re-examined in a state-of-the-art climate model which reproduces the climatological and intraseasonal features of the observed monsoon (Roxy et al. 2012). The observed co-variability and rate of change of convection with respect to SST is replicated in the model simulations (Fig. 2d, e). As a result, a notion of an upper threshold does not hold for the tropical monsoon basins, for the entire range of observed SSTs (26–31 °C). Instead, precipitation is found to increase (nearly) monotonously, throughout the SST range. This is specifically significant since the mean SSTs over the basins under consideration are mostly over 28.5–29.5 °C during the monsoon season (Fig. 2c).

Increased SSTs tend to increase the equivalent potential temperature (θ_e, analogous to moist static energy) over the surface, thereby destabilizing the lower atmospheric column, a condition favorable for enhancing the convection (Sobel 2007; Roxy and Tanimoto 2007, 2012; Wu 2010; Lau and Waliser 2012). This mechanism may be responsible for the precipitation to respond favorably whenever there is a positive change in SST. However, even if the SSTs over a region are conducive for increased convective activity, subsidence forced by nearby (or remotely generated) convective cells of the upper air circulation could overplay and suppress the local convection (Lau et al. 1997). Hence, to weigh their respective roles, the lower atmospheric (1,000 hPa) equivalent potential temperature (θ_{e1000}) is used for representing the influence of SST on lower atmospheric stability and resultant convection (Roxy and Tanimoto 2007); and the upper atmospheric (200 hPa) divergence is utilized for typifying the relative role of large scale circulation on convection (Lau et al. 1997). θ_{e1000} is a measure of the moisture and temperature of the lower atmosphere, with warm moist air resulting in unstable conditions and enhanced convection, or cold dry air weakening it. The divergence fields provide an idea of whether the upper atmospheric conditions favor (ascending motion, positive divergence) or weaken (subsidence, negative divergence) the convection.

Figure 3 compares the variability of lower atmospheric equivalent potential temperature and upper atmospheric divergence along with precipitation, at the observed lags with respect to SST. The θ_{e1000} is examined at simultaneous lag with SST because near surface equivalent potential temperature immediately responds to SST. The upper level divergence is examined at the same lags for precipitation, as no definitive lags are observed between these two variables. The results here show that lower level atmospheric instability monotonously increases along with the SST, ensuing enhanced convection throughout. It is however, seen that the fluctuations in the SST-precipitation co-variability is regulated by the large scale atmospheric dynamics, as depicted by the upper atmospheric divergence at 200 hPa. The curve with respect to precipitation closely follows the variability in the upper level divergence. This implies that a dip in upper level divergence, which essentially indicates subsidence at these levels, results in suppressing or weakening the convection.

The analysis in the current study focus on the mean response of precipitation for every 0.1 °C bin of SST. However, there exists a precipitation variability on a finer scale, within each 0.1 °C SST bin, assessed by the standard deviations of precipitation (at determined lags) for each 0.1 °C SST (Fig. S1). The results show that standard

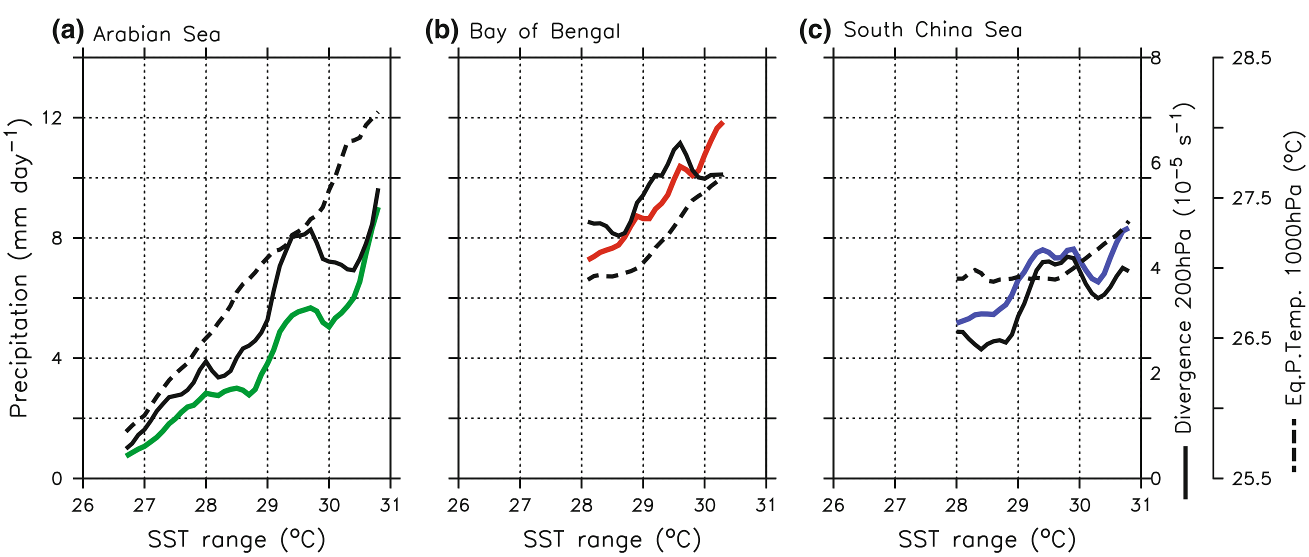

Fig. 3 Observed variation of precipitation (color, mm day^{-1}), divergence at 200 hPa (*solid*, 10^{-5} s^{-1}) and the equivalent potential temperature at 1,000 hPa (*dashed*, °C) with SST (°C) over the **a** Arabian Sea, **b** Bay of Bengal, and the **c** South China Sea, at observed lags

deviations increase with SST, with maxima observed at around 29–30 °C of SST. The precipitation variability is large at these SSTs probably because both clear sky and clouded conditions are associated with active precipitation (Zhang 1993). The large variability at higher SSTs points out the possible nonlinearities of the relationship within each 0.1 °C bin, and that factors other than SST might also play a role on the precipitation variability on finer scales. This may also be seen as a feedback to the SST-precipitation relationship, whereby active convection and related processes regulates the mean response of convection to SST.

3.2 SST-precipitation relationship in a changing climate

The present study is indicative of an increased precipitation in a changing climate with increased SSTs. This has been pointed out by previous studies for the global tropics, as well as the coupled model intercomparison project (CMIP) model simulations, and has been included in the Intergovernmental Panel on Climate Change—Assessment Reports (IPCC AR4/AR5) (Turner and Annamalai 2012; IPCC 2013; Ma and Xie 2013; Roxy et al. 2013). Though recent studies point out the increasing frequency of extreme rainfall events for the Asian monsoon in a changing climate, a few studies have reported that the monsoon circulation is weakening (IPCC 2013; Turner and Annamalai 2012; Zhou et al. 2008; Ma and Xie 2013; Krishnan et al. 2013). It would therefore be interesting to elucidate whether the precipitation over the monsoon regions would increase with rising temperatures corresponding to growing mixing ratios of greenhouse gases such as carbon dioxide (CO_2).

Numerical experiments were carried out and comparisons done between simulations with mixing ratios of CO_2 fixed at present day ($1 \times CO_2$ ~398 ppm) and doubled ($2 \times CO_2$, ~796 ppm) levels (Fig. 4a, b). Results from the future climate projections show a statistically significant (greater than 90 % levels) increase of up to 2–3 mm day^{-1} for regions over the Indian Ocean and the South China Sea, with an increase of 1–2 °C of SST. It may seem that there is a mismatch in the regions of maxima of SST and precipitation increase. This is because the regions of maximum precipitation tends to be located at the ascending branches of the tropical circulation (Lau et al. 1997). It is possible that the weakening of the monsoon circulation in a changing climate (IPCC 2013) is compensated by the enhanced convection due to warmer ocean temperatures. This balancing act might give a clue on why the monsoon precipitation over the last several decades has not shown any significant trend despite a slowdown of the circulation. The results from the future climate projections are similar to those from the present day observational analysis which indicates an increase of 2–3 mm day^{-1} in precipitation for an increase of 1 °C in SST (Fig. 4c).

4 Summary and discussion

The SST-precipitation relationship over the Asian monsoon domain is re-examined, and given a new perspective in the present study, using recent high quality satellite data and climate data simulated by a state-of-the-art coupled model. Instead of using monthly data, daily data with appropriate lead-lags, for each basin, are utilized to re-examine the co-

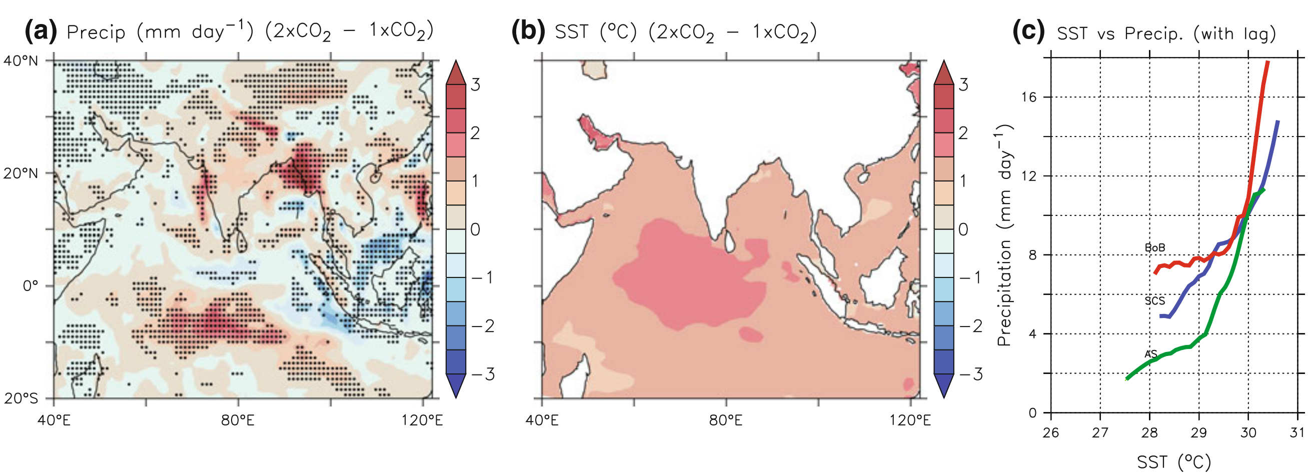

Fig. 4 Differences in the climatology between $2 \times CO_2$ and $1 \times CO_2$ model simulations, for **a** precipitation (colors, stippling indicates significance greater than 90 % level; mm day^{-1}) and **b** SST (colors indicate significance greater than 90 % level; °C) over the Asian monsoon region, during June–September. **c** Variation of precipitation (mm day^{-1}) with SST (°C) at lags over the Arabian Sea (*green curve*), Bay of Bengal (*red curve*) and the South China Sea (*blue curve*), for June–September, for the $2 \times CO_2$ model simulations. The simulated lags at maximum regression coefficient, for the $2 \times CO_2$ runs are 7, 12 and 11 days, for AS, BoB and SCS, respectively

variability between SST and precipitation. This is based on the realization that the SST-precipitation relationship has a lag, that too with a spatial variability, over the monsoon basins.

For the last three decades, there has been a classical figure of the SST-precipitation relationship, portraying an increase of precipitation along with an increase in the SST, until the SST reaches an upper threshold of about 29 °C, beyond which the relationship breaks down. The implications with respect to the above mentioned hypothesis are critical for the Asian summer monsoon since the SSTs over the monsoon basins (e.g.: Indian Ocean, west Pacific) during summer is mostly above such a threshold. The current study using a novel perspective, points out the illogicality behind it, and draws out a new figure for the SST-precipitation relationship. The study, taking into account the appropriate lead/lags between SST and precipitation at each monsoon basin, shows that precipitation increases throughout the range of observed SSTs over these basins (26–31 °C) and that there is no upper threshold for such a relationship. Besides rectifying the understanding of the SST-precipitation co-variability, the current study quantifies the relationship—a 2 mm day^{-1} increase in rainfall for every 1 °C rise in SST, consistent across all the monsoon basins, both for the observations and the model simulations.

SSTs over the Indian Ocean and west Pacific show variability on intraseasonal timescales, with a change of up to 1–2 °C within a week or two. The atmospheric response to such SST variability is evident in a few days, with the maximum response in 3–12 days, depending on the region. This would imply that including realistic ocean–atmosphere coupling is crucial for short-term monsoon weather forecasts (seasonal monsoon predictions already employ coupled models)—a decisive factor for nearly one-half of the world population whose socio-economic activity is influenced by the Asian summer monsoon variability. Some previous studies (e.g.: Rajendran et al. 2012) asserted that the atmospheric general circulation models (AGCM) can capture the SST-precipitation relationship as in the coupled model based on monthly mean. Recent studies (Sahai et al. 2013; Sharmila et al. 2013), however, shows that the AGCMs forced with monthly (or even daily) SSTs are unable to capture the time response or the amplitude of the observed lags.

The sensitivity results are also valid in a changing climate with increasing SSTs. This is supported by model simulations which indicate an increased precipitation over the tropical monsoon regions, in a global warming environment with increased SSTs. It is therefore meaningful to conclude that the sensitivity of precipitation to increased SSTs acts as a balancing factor for the weakening monsoon circulation over the last few decades. The analysis here hence suggests that SST variability and its response on the monsoon precipitation are significant, in a quantifiable manner, seamlessly through all the timescales—from short-term intraseasonal to long-term climate scales.

It is to be noted that the large scale circulation features has a role in modulating the SST-precipitation relationship presented in this study. For example, a significant dip in upper level divergence, which essentially indicates subsidence at these levels, might result in suppressed convection over that region, as shown in Fig. 2. The upper level divergence was examined at the same lags as precipitation, and it can be argued that the resultant divergence is a consequence of the convection. A lead-lag analysis between divergence and precipitation was carried out, but no definitive lags were observed on daily timescales, sufficient enough to explain the influence of divergence on precipitation or vice versa. It is also worth noting that SST has a role in influencing the large-scale circulation including the upper level divergence (Lau et al. 1997). However, is not easy to isolate the mutual influence between these two variables as divergence is tightly coupled with convection also.

It is obvious (Fig. 1c) that there exists a SST-precipitation relationship at negative lags also, whereby convection (the presence or absence of it) influences the SST variability. This is one of the reasons why a simultaneous correlation of the relationship fails to give conclusive results, as it includes both the positive and negative aspects of the relationship. Role of convection on SSTs has been investigated by several earlier studies (Zhang 1993; Waliser 1996; e.g., Sud et al. 1999). The perspective might get different in this case also, when the lead-lag relationship is considered. The processes involved in such a relationship is very much different from the effect of precipitation/convection on SST. It is also necessary to point out that the changes in convection regulates the SST (and its upper limits) and in turn the SST-precipitation relationship. The feedback of convection on SST requires a detailed analysis on its own, bringing out the step by step processes involved, and may be included in a future study.

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