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Key Points:
- Equatorial Pacific sea surface temperature bias contributes to double ITCZ bias in climate models
- Interpretation of future tropical rainfall projections requires care as double ITCZ bias affects precipitation trends
- Improvement of bias in equatorial Pacific sea surface temperature may reduce uncertainty in rainfall projections

Supporting Information:
- Supporting Information S1

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Tropical Pacific SST and ITCZ Biases in Climate Models: Double Trouble for Future Rainfall Projections?

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Abstract The double Intertropical Convergence Zone bias remains a persistent problem in coupled general circulation model simulations. Due to the strong sea surface temperature (SST)-convection relationship in the tropics, precipitation biases are sensitive to background SST. Using historical simulations of 24 coupled general circulation models and an atmospheric general circulation model, we show that cold equatorial SST biases at least exacerbate double Intertropical Convergence Zone biases in the Pacific. A linear regression model is used to demonstrate that improved predictability of precipitation trends is possible with such model-dependent information as mean-state SST biases accompanying projected SST trends. These results provide a better understanding of the root of the double Intertropical Convergence Zone bias and a possible path to reduced uncertainty in future tropical precipitation trends.

Plain Language Summary Dozens of complex computer models of the climate system (accounting for both atmosphere and ocean) are used for climate change predictions over the coming decades as anthropogenic emissions of greenhouse gases persist. These computer models are essential yet imperfect. Two well-known mismatches (i.e., biases) in models that have persisted for many years include (1) too cold sea surface temperature (SST) along the equatorial Pacific Ocean and (2) excessive precipitation south of the equator, which appears as a double-peaked precipitation pattern known as the double Intertropical Convergence Zone (ITCZ). These are commonly referred to as the “cold tongue bias” and “double ITCZ bias,” respectively. Our analysis confirms that they are closely related in models; the worse the cold tongue bias is, the more the ITCZ is split into two. We also found that predicted trends in tropical rainfall depend on these biases; models with the least severe SST bias will improve relative to today's climate as SST warms, whereas the double ITCZ in models with the most severe biases will remain the same even as equatorial SSTs warm. Finally, we demonstrate that rainfall predictions can be improved if information about biases is accounted for.

1. Introduction

Convection and precipitation are strongly coupled over the tropics (Neelin & Held, 1987), such that uncertainties in resolving convection in coupled general circulation models (CGCMs) continue to result in a biased simulation of precipitation. These uncertainties include transitions between shallow and deep convection (Wang et al., 2015) and a smaller sea surface temperature (SST) threshold for triggering deep convection (Bellucci et al., 2010). Future changes of tropical Pacific precipitation are largely dependent on the response to changes in underlying SST (Power et al., 2013; Xie et al., 2010). Moreover, future precipitation changes in the tropical Pacific are controlled by two key processes—(i) a dynamic response from the overall slowing of tropical circulation and (ii) a “wet get wetter” thermodynamic response (Chadwick et al., 2013; Held & Soden, 2006; Seager et al., 2010; Vecchi & Soden, 2007). The underlying SST field can affect all these processes; therefore, the details of SST anomaly can largely impact precipitation changes (Chadwick et al., 2013; Kent et al., 2015).

Intertropical Convergence Zone (ITCZ) is the zonally oriented tropical precipitation band with the most intense rainfall globally (Schneider et al., 2014; Waliser & Gautier, 1993). Despite the seasonal cycle of solar radiation, the persistent displacement of the ITCZ north of the equator is a key asymmetric feature of global climate. Due to this hemispheric asymmetry, the annual-mean ITCZ lies ~5° north of the equator at most

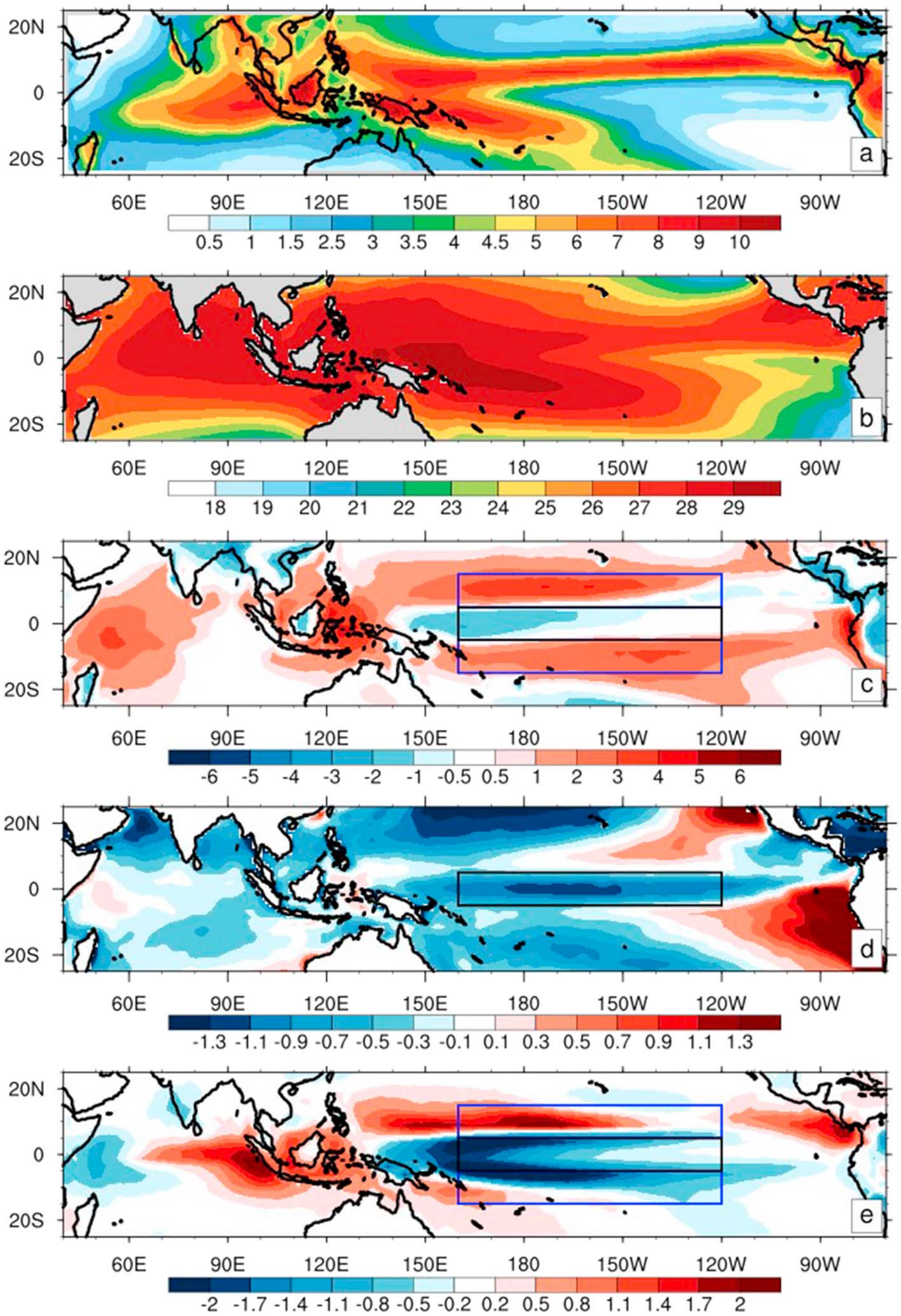

Figure 1. Annual climatology, and biases in precipitation (in mm·day^{-1}), and sea surface temperature (SST; in °C) in historical simulations. Observed climatology of (a) precipitation and (b) SST; multimodel ensemble annual bias of (c) precipitation and (d) SST; and (e) linear regression of precipitation bias onto annual SST bias (in mm·day^{-1}·°C^{-1}) averaged over 5°S–5°N, 160°E–120°W (EB) for 24 CMIP5 models. The sign of regression coefficient is reversed in (e). Black boxes in (c)–(e) denote the domain for the SST and precipitation bias calculations. Blue boxes in (c) and (e) denote northern and southern boxes for calculation of double-ITCZ bias.

longitudes, especially in the Pacific (Figure 1a). The annual mean northward displacement of the ITCZ is generally attributed to the excess annual mean heating of the northern hemisphere by the Atlantic meridional overturning circulation (Marshall et al., 2014), but is sensitive to regional SST anomalies (Adam, Schneider, et al., 2016).

The double ITCZ is a characterized as the proclivity of the CGCMs to produce excessive precipitation south of the equator, which, in the annual mean, gives the appearance of a nearly symmetric bimodal precipitation distribution straddling the equator (Adam et al., 2018; Lin, 2007; Zhang, 2001; Zhang et al., 2015), rather than a dominant peak north of the equator in observations. A southern ITCZ mostly occurs during boreal spring in the eastern Pacific, whereas, in the western Pacific, an excessive double ITCZ that straddles the equator is seen year-round (e.g., Adam et al., 2018). However, a northern ITCZ is observed in all seasons (Ma et al., 1996). A double ITCZ can also emerge in some climate models in the Atlantic sector, and generally in aqua planet simulations (e.g., Zhou & Xie, 2015). CGCMs in Coupled Model Intercomparison Project phase 5 (CMIP5) continue to suffer from the double ITCZ bias (e.g., Zhang et al., 2015), which has been linked to a multitude of factors, such as tropical circulation, future precipitation projections under climate change (Li & Xie, 2014), and climate sensitivity (Tian, 2015). Additionally, CGCMs simulate a cold tongue SST bias over the tropical Pacific (De Szoeke & Xie, 2008; Li & Xie, 2014; Richter et al., 2016), which is another persistent problem for a realistic simulation. However, due to the paucity of observations with sufficient temporal and spatial coverage, CGCMs remain a key tool for better understanding historical and future climates (Yang et al., 2018). The biases in cold tongue SST and ITCZ and the unclear relationship within them impose a major barrier to the realistic simulation of tropical precipitation trends in CGCMs not only over the tropical Pacific but also over the entire globe through, for example, Rossby wave responses to tropical heating (Gill, 1980; Trenberth et al., 1998). Moreover, the double ITCZ impacts the simulation and predictability of different modes of seasonal-to-interannual climate variability, such as the Madden-Julian Oscillation and the El Niño–Southern Oscillation (Guilyardi et al., 2003; Inness & Slingo, 2003; Wittenberg et al., 2006), limiting the certainty of CGCMs predictions, particularly the future trends in the face of anthropogenic radiative forcing.

The double-ITCZ bias, that is, excessive tropical precipitation south of the equator along with underestimated equatorial precipitation, leads to a major barrier for representing tropical climate dynamics in CGCM simulations (Bellucci et al., 2010; Lin, 2007; Oueslati & Bellon, 2015; Song & Zhang, 2018; Xiang et al., 2017). Several underrepresented dynamical and thermodynamical feedback, such as Bjerknes feedback (Li & Xie, 2014; Lin, 2007), SST-shortwave flux feedback (Lin, 2007), SST-latent heat flux feedback (Lin, 2007; Song & Zhang, 2016), and zonal SST gradients in the Pacific and Atlantic (Lin, 2007; Siongco et al., 2015), are known to affect the double-ITCZ bias in CGCM simulations. A double-ITCZ bias in CGCMs can emerge from several factors, such as the choice of convective parameterization scheme (Hirota et al., 2011), convective mixing (Möbis & Stevens, 2012; Song & Zhang, 2018), or from atmospheric transient eddies (Xiang et al., 2018). Additionally, a precipitation bias in CGCM simulations can emerge due to biases in tropical SST pattern associated with ocean current in the model itself (Wang et al., 2015). Indeed, Hwang and Frierson (2013) have shown that biases in cross-equatorial energy transport are linked to precipitation biases south of the equator. However, their suggestion that Southern Ocean low cloud biases are the cause of the biases in the cross-equatorial energy fluxes has since been shown to be unsupported (Adam et al., 2018; Hawcroft et al., 2017; Kay et al., 2016).

Because of structural diversity and different mean states of each CGCM, quantifying the origin of the double ITCZ remains a challenge. This also leads to a causal dilemma: is the double ITCZ a consequence of evolving SST biases or is the SST bias itself driven by double-ITCZ bias? While the later direction of causality may be important for some contexts, such as the study of cool climates with scarce precipitation (e.g., the Galapagos islands; Lietzke et al., 2001; Gu et al., 2005), we are driven here to investigate the possible role of the SST bias on the double-ITCZ bias. Earlier studies (e.g., Song & Zhang, 2016, 2018) investigated the southeastern Pacific SST bias on the double-ITCZ bias in one CGCM by prescribing local SST forcing. Few other studies (e.g., Ma et al., 1996; Qin & Lin, 2018) argued for an influence of marine low clouds. However, these studies neither investigated the direct response of SST forcing over the cold tongue region, nor studied SST response in a diverse ensemble of CGCMs.

In this study, we aim to investigate the relationship among mean-state biases in recent generation CGCMs, particularly between the double-ITCZ bias and the cold equatorial Pacific SST bias, as well as the implications for simulated tropical precipitation trends. Our study focuses on the aspects of year-round double-ITCZ bias present over central and western Pacific, however, does not involve seasonal double-ITCZ pattern over eastern Pacific or Atlantic sector during boreal spring.

2. Models and Methods

2.1. Observations and CMIP5 Models

Monthly SST and precipitation output from historical runs for the period 1861–2005 from 24 CMIP5 models (Taylor et al., 2012) are employed in this study. A detailed list of CMIP5 models is provided in Table S1. For annual mean bias calculations, we used monthly precipitation data from the Global Precipitation Climatology Project (Adler et al., 2003) and SST from COBE SST version 2 (https://www.esrl.noaa.gov/psd/data/gridded/data.cobe2.htm). Annually resolved data for these variables were then transformed into a common grid of 2.0° × 1.5° using bilinear interpolation for calculating multimodel composites. Biases and trends in SST and precipitation are calculated over the equatorial Pacific box (EB; 5°S–5°N, 160°E–120°W).

The inadequacy of clear definitions and the use of various indicators in different studies to characterize the double-ITCZ bias have made understanding the key issues to address problematic (Popp & Lutsko, 2017). Furthermore, the earlier defined hemispheric asymmetry index, equatorial precipitation index (e.g., Adam, Bischoff, et al., 2016), or southern ITCZ index (e.g., Tian, 2015) cannot explain aspects of the double-ITCZ bias in the annual mean. Therefore, we construct a new, simpler double-ITCZ bias index to investigate the severity of the double-ITCZ pattern over the central Pacific in annual mean precipitation. We define a double-ITCZ bias index using the precipitation bias over the following three boxes: northern Pacific box (NB; 5°N–15°N, 160°E–120°W), Southern Pacific box (SB; 15°S–5°S, 160°E–120°W) and EB, such that

$$\text{Double ITCZ bias} = \frac{(\text{NB} + \text{SB})}{2} - \text{EB} \tag{1}$$

The magnitude of double-ITCZ bias index varies depending on the zonal boundary of these boxes, but the relationships presented in the paper do not (see Figure S1 for the impact of box size in zonal direction). See Figure 1 for illustrations of these boxes relative to time-mean SST and precipitation fields as well as biases and their dependence on one another. In this paper, we show the annual mean climatology of all fields throughout.

2.2. AGCM Experiments

Atmospheric general circulation model (AGCM) experiments with prescribed SSTs were performed to examine the impact of different equatorial Pacific SST biases on tropical Pacific precipitation, thereby testing the hypothesis that SST biases regulate the magnitude of the simulated double ITCZ. The AGCM used in this study is ECHAM4.6 from the Max Planck Institute in Hamburg (HAM), a branch of the European Centre (EC) for Medium Range Weather Forecasts (Roeckner et al., 1996). We ran this model at T42 resolution (~2.8° × 2.8°) with 19 vertical levels and daily outputs are obtained. Vertical diffusion is calculated based on turbulent kinetic energy using a high-order closure scheme and surface turbulent fluxes are calculated from Monin-Obukhov similarity theory. Cumulus parameterization of this model is based on the bulk mass flux concept (Tiedtke, 1989). ECHAM4.6 has been widely used to study atmospheric responses to tropical SST anomalies (Fu et al., 2003; Xiang et al., 2013; Zhang & Li, 2017; Zhang & Karnauskas, 2017).

We have performed seven experiments differing only in the prescribed monthly climatological SST fields. The control run was forced with the observed SST climatology (i.e., bias = 0 °C), and six experiments with idealized biases (BIAS) of −2.0, −1.5, −1.0, −0.5, 0.5, and 1.0 °C imposed over the domain 5°S–5°N, 150°E–82°W were also performed. While the magnitude of the SST bias imposed over the equatorial Pacific region varies in the six different BIAS experiments, the baseline SST climatology over other regions remains the same. To reduce the possible impact of spurious SST gradients along the boundaries of the prescribed biases, we applied a simple taper barrier with one half the magnitude of the SST anomaly instead of zero SST anomaly. For each AGCM experiment, the model was integrated for 30 years, and the first 5 years were discarded given that it takes a few years for this model (like most AGCMs) to reach an equilibrium state with the SST forcing (Zhang & Karnauskas, 2017). As with the CGCMs and observations, we only show the annual mean climatology in this study.

2.3. Linear Regression Model

Finally, we used a simple linear regression model to explore the possible improvement of the predictability of precipitation trends based on SST biases and SST trends in CMIP5 models as predictors. Response (y_i) of ith CMIP5 model in a linear regression model can be expressed as below:

$$y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \varepsilon_i \tag{2}$$

where β_0 is the constant terms in the model, $\beta_k (k = 1, 2)$ is the kth coefficient, X_{ki} $(k = 1, 2)$ is the ith CMIP5 model on the kth predictor variable, and ε_i is the ith noise term, that is, random error. Here X_1 and X_2 are the SST bias and the SST trend over EB, respectively. Based on this regression model and using the SST bias and trend over the EB as the predictors, we calculate the estimated coefficients (i.e., linear model fit). Then, a predicted precipitation trend value over the EB is calculated using the linear model fit value and the predictor (SST bias and SST trend), based on trained discriminant analysis classification model fit. The predicted response is computed for the entire time span covered by the predictors, and it is assumed that the various classes generate data based on different Gaussian distributions (see Eisenbeis & Avery, 1972 for details about discriminant analysis classification).

3. Results

Regional details of tropical SST distributions (Figure 1b) and continental configuration have an important influence on the position and shape of the ITCZ. The simulated precipitation in CGCMs is not only biased, but the bias magnitude also varies from model to model (see Figures S2 and S3 for individual model bias in precipitation). The multimodel mean bias (Figures 1c and 1d) clearly shows the coexistence of double-ITCZ pattern along with equatorial Pacific cold tongue SST bias (see Figures S4 and S5 for individual model bias in SST). Tropical precipitation biases in CGCMs interact with SST biases generated by interaction with the ocean (Xiang et al., 2017). Regression of precipitation bias fields on SST bias averaged over the EB (Figure 1e) suggests that precipitation biases covary with SST bias over the EB and inversely vary with the off-equatorial zones where a double ITCZ exits. This result highlights the strong association between spatially coherent precipitation biases and equatorial SST biases, particularly over the western Pacific. However, a negative regression coefficient value over a large portion of the SB in Figure 1e may be related to the nonparametric nature of this regression calculation and involves intermodel differences. Since SST and atmospheric energy budget are strongly correlated near the equator, the link between the cold SST biases and excessive double ITCZ can be explained using the energy flux framework, which predicts stronger double ITCZ in the western Pacific (Adam et al., 2018).

A stronger cold SST bias appears to exacerbate the double-ITCZ bias (Figure 2a). Furthermore, precipitation trends in CGCMs are statistically related to the SST bias by a positive linear correlation (Figure 2b), implying (but not yet proving) a possible control of SST bias on precipitation trends. As the double-ITCZ bias includes a dry precipitation bias over the equatorial Pacific, SST biases are also closely related to an increase in dry precipitation bias over EB (Figure 2c). While the SST bias becomes positive (i.e., less severely biased), the equatorial dry precipitation bias is also alleviated. In agreement with these relationships, a severe double-ITCZ bias is associated with a lower precipitation trend over the EB. These results within mean-state biases and trends in CGCMs suggest possible interdependencies of precipitation trends with other biases as previously shown. We therefore hypothesize that the SST bias over the equatorial Pacific in CGCMs has an important role on the emergence of a double-ITCZ bias with implications for the simulated equatorial precipitation trend. A larger positive SST trend over the equatorial Pacific is likely to drive a larger positive precipitation trend due to a strong relationship between SST and convection merely following the Clausius-Clapeyron equation. However, a severely cold SST bias diminishes the ability of the same incremental SST trend to influence the precipitation trend. In other words, for warmer initial SST, there is greater potential for rainfall to respond to further incremental changes in SST.

It is difficult to disentangle SST-precipitation relationships from coupled simulations due to the challenge of isolating the SST-forced atmosphere response and intrinsic variability of the atmosphere (He et al., 2018) and due to ocean–atmosphere coupling. In other words, correlation is not equivalent to causation. The previous discussion (Figure 2) provides statistical support to our hypothesis of the control of SST bias

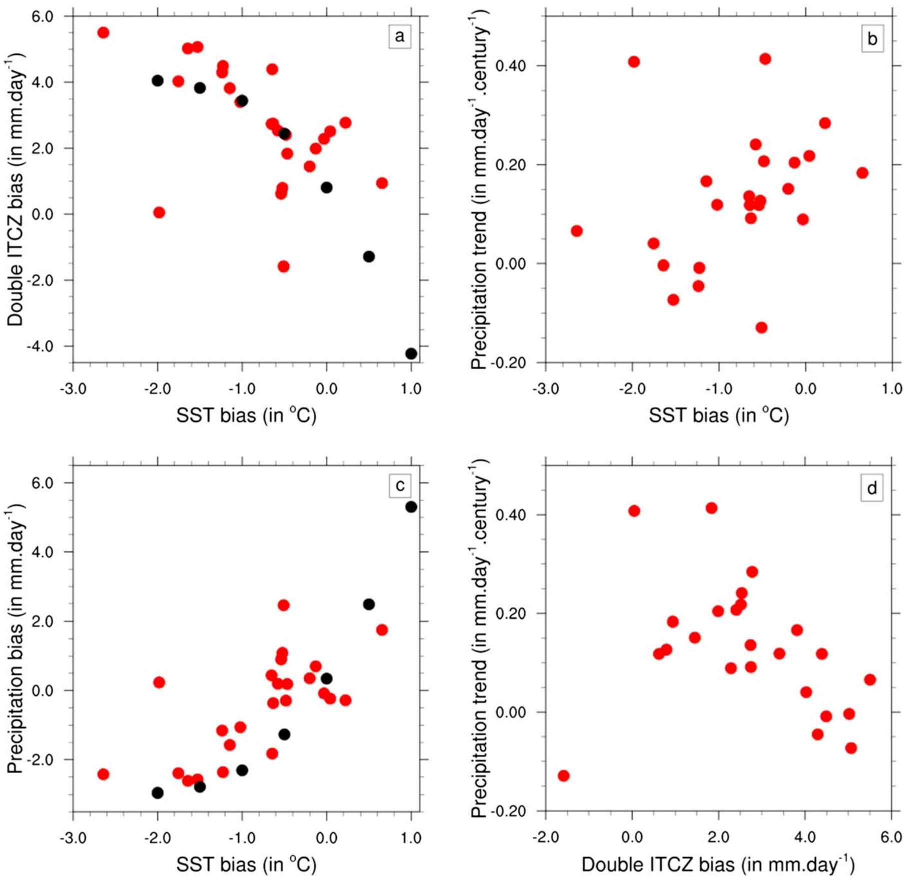

Figure 2. Relationship among mean-state annual biases and trends in historical simulations. Scatterplots for (a) SST bias versus double-ITCZ bias, (b) SST bias versus precipitation trend (in mm·day^{-1}·century^{-1}), (c) SST bias versus precipitation bias, and (d) double-ITCZ bias versus precipitation trend (mm·day^{-1}·century^{-1}). Red and black dots denote each CMIP5 model and each AGCM experiments, respectively. SST biases and precipitation bias/double-ITCZ bias are in °C and mm·day^{-1}, respectively.

over double-ITCZ bias and precipitation bias. To test the hypothesis more systematically, we carried out a set of idealized AGCM experiments as described in section 2. The AGCM experiments strongly agree (black dots in Figures 2a and 2c) with the CGCM's implied dependence of the double-ITCZ bias and the precipitation bias on the SST bias. However, the double-ITCZ bias becomes less sensitive in the BIAS experiments beyond −1 °C. Because of structural diversity across models, the mean state of each CGCM is different (red dots), whereas the AGCM experiments without ocean–atmosphere coupling and no changes in model configuration involve less complexity than CGCMs. Additionally, nonlinear double-ITCZ characteristics in AGCM experiments may be a consequence of reduced sensitivity to decreased (increased) precipitation bias over the EB (NB and SB) beyond −1 °C SST bias (black dots in Figure 2a). This nonlinear response of precipitation bias to SST bias needs further study. It is noteworthy that despite intermodel spread in the location of the southern lobe of the ITCZ (akin to the South Pacific Convergence Zone or SPCZ in the real world) in CMIP5 simulations, the multimodel mean bias pattern places the mean location toward the eastern Pacific. This may be related to the incomplete representation of ocean dynamics that have an important role in ocean–atmosphere coupling and trends in CGCM simulations (Coats & Karnauskas, 2018; Karnauskas et al., 2007; Karnauskas et al., 2012).

While the above analysis demonstrates the critical role of SST biases on precipitation biases over the tropical Pacific including those manifested as a double ITCZ, the spatial patterns of precipitation biases (Figure 3) show the response to different SST bias levels over the cold tongue region, and indicate the increase of severity of double-ITCZ pattern. Figure 3 indeed clearly demonstrates the crucial role of the

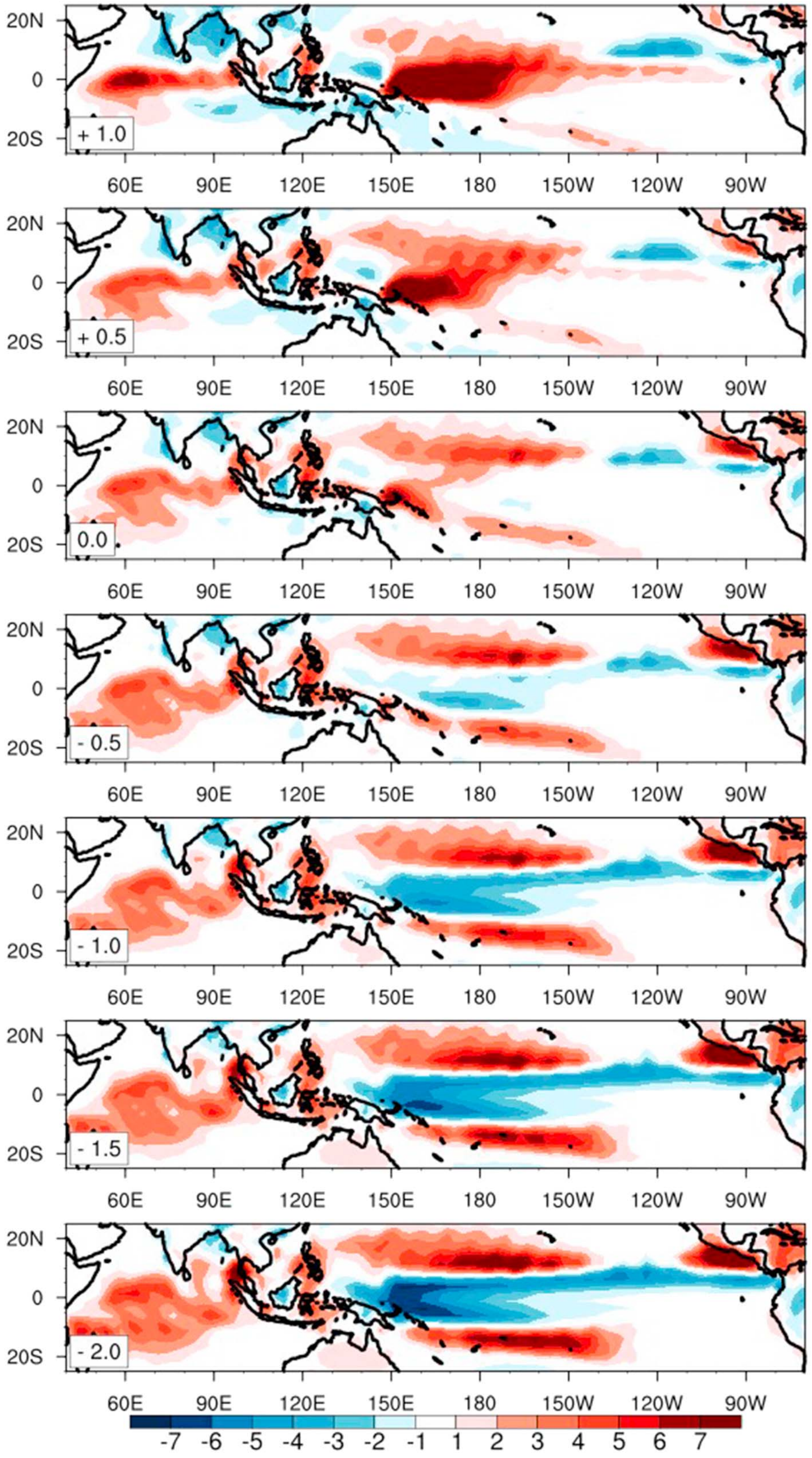

Figure 3. Annual mean precipitation bias (in mm·day^{-1}) from each AGCM experiments. Legends in each subplot denote the applied SST bias in SST forcing over equatorial Pacific. Bias level 0.0 indicates control experiment forced with observed SST.

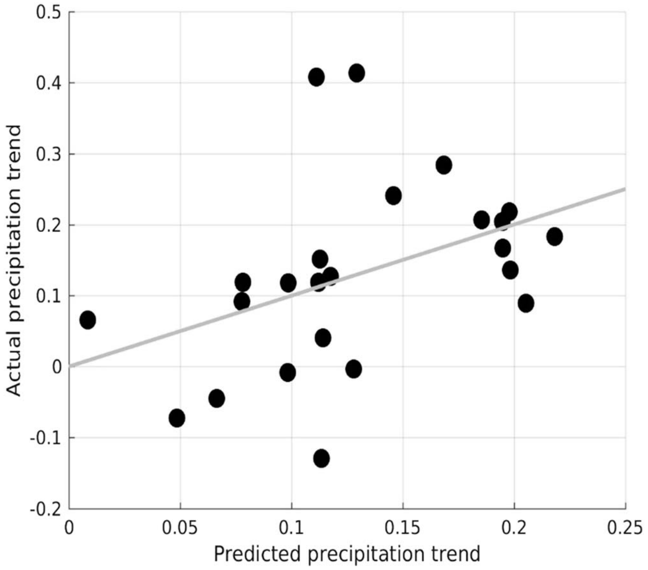

Figure 4. Precipitation prediction using a linear regression model. Scatterplot between predicted centennial precipitation trend (in mm) and actual simulated centennial precipitation trend (in mm) from historical simulations. Predicted precipitation trend is calculated using SST bias and SST trend as the predictor. Black dots denote each CMIP5 model. The regression line is overlaid on the scatterplot. The correlation coefficient between predicted precipitation and actual precipitation is 0.43 at more than 95% confidence level.

SST bias over equatorial Pacific on the emergence of a double-ITCZ bias. We cannot rule out the possibility of the control of other potential factors on the emergence of the double ITCZ. Nonetheless, our results strongly suggest that SST bias has at least one of the crucial controls on the double-ITCZ bias. Consistent with several earlier studies (e.g., Hirota et al., 2011), the control experiment also suggests a possible emergence of a double-ITCZ pattern even without a SST bias. This implies that at least a substantial source of double-ITCZ pattern lies in the atmospheric component of CGCMs. Despite this fact, our results highlight how a mean-state equatorial SST bias can control the severity of the double-ITCZ pattern, indicating possible consequence of precipitation trends in CGCMs.

We further explore the sensitivity of precipitation biases to SST biases in CGCMs over the equatorial Pacific (Figure S6) and how it depends on the regime (i.e., warm pool versus cold tongue). We used longitude as a variable spanning such regimes, and calculated the bias dependency for several 10° longitude-wide zones across equatorial Pacific. Results clearly suggest that the sensitivity of precipitation bias to SST bias is greater over the western and central equatorial Pacific than eastern equatorial Pacific. This feature is also seen in Figure 1e. The higher sensitivity of precipitation over these regions of warmer mean SST is likely related to a greater change in surface pressure for the same incremental change in SST, again simply invoking on the Clausius-Clayperon equation. In general, the wet bias decreases (or dry bias increases) with an increase in cold bias (Figure S6). However, unlike a general characteristics precipitation bias increases (i.e., increases wet bias) up to the threshold SST bias of 0 °C and then decreases with an decrease in the SST bias (i.e., increase in the cold SST bias) over the western Pacific warm pool region (140°E–150°E box), which may be related to additional responses of land-atmosphere interactions and weak SST-convection relationship over this region. Contrary to the central and eastern Pacific, the SST-convection relationship over the western Pacific region is largely controlled by the large-scale dynamics, rather than by local thermodynamics (Waliser & Graham, 1993; Wu & Moncrieff, 1999). Earlier studies reported that deep convection over western Pacific warm pool region (where maximum SSTs occurs) is not correlated with SST variations over the same region (Fu et al., 1992), even inversely related with the increase of SST beyond a certain threshold (Waliser & Graham, 1993).

The above results directly imply that improved prediction of tropical precipitation trends may be possible with simple knowledge of model-dependent tropical climate biases. Using a linear regression model and considering spatially averaged SST biases and trends over the EB region as the only predictors, we calculate a predicted value of precipitation trends that are significantly correlated (correlation coefficient 0.43 at more than 95% confidence level) with the actual simulated precipitation trend (Figure 4). This is not the case if only the SST trend is used as the predictor (correlation coefficient 0.25) or only the precipitation bias is used as the predictor (correlation coefficient 0.31). It is noteworthy that this approach is not likely to explain the entire range of interactions between mean-state biases and precipitation trends, as the CMIP5 models are fully coupled and have important structural differences. Nonetheless, this result suggests a possible way to adjust or constrain the simulated precipitation trends in an “off-line” way according to their dependence on mean-state biases described herein.

4. Summary and Conclusion

Using historical simulations from 24 CMIP5 climate models, we explored the potential relationship between the double-ITCZ and equatorial SST biases in the tropical Pacific sector, and its implications for tropical precipitation trends in CGCMs. Our results suggest that a cold equatorial SST bias linked to the emergence of a double-ITCZ bias in CGCMs. Due to a strong SST-convection relationship over the tropical Pacific, the double-ITCZ bias in CGCMs is sensitive to background SST, which is further supported by a set of AGCM experiments targeted at this hypothesis. The AGCM experiments with different SST biases demonstrate this clear dependence.

SST and precipitation over the equatorial Pacific region are critical for a multitude of factors, not only for CGCM biases but also for its impact on climate over various regions of the globe through remote teleconnections. For example, equatorial Pacific SST is strongly connected with El Niño–Southern Oscillation diversity, which is further known to have a profound influence on the weather and climate around the globe (e.g., McPhaden et al., 2006). Moreover, several recent studies reported the increase in the frequency of central Pacific El Niño events in a climate-changing scenario (e.g., Lee & McPhaden, 2010). Furthermore, as global warming-induced precipitation changes are likely to occur mostly over equatorial Pacific Ocean (Zhou & Xie, 2015), it is meaningful to have a better understanding of relationships between the SST and precipitation biases in CGCM simulations and to improve the simulated precipitation trends in CGCMs.

The presented results highlight not only the important implications of SST biases on historical simulation of precipitation but also the likely impact on future precipitation projections. Our study provides a simple framework for reducing uncertainty in rainfall projections. It may be possible to increase the reliability of precipitation trends in CMIP5 models given such mean-state bias information, all of which is available prior to CGCM biases being completely resolved by the model development community.

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