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Key Points:
- The double ITCZ problem in CMIP5 models is tightly linked to the tropical SST bias
- The severity of the double ITCZ problem in coupled models can be predicted by using the tropical net surface heat flux in AMIP simulations
- The largest source of the DI bias is from the tropics and from atmospheric models

Supporting Information:
- Supporting Information S1

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Predicting the severity of spurious "double ITCZ" problem in CMIP5 coupled models from AMIP simulations

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Abstract The severity of the double Intertropical Convergence Zone (DI) problem in climate models can be measured by a tropical precipitation asymmetry index (PAI), indicating whether tropical precipitation favors the Northern Hemisphere or the Southern Hemisphere. Examination of 19 Coupled Model Intercomparison Project phase 5 models reveals that the PAI is tightly linked to the tropical sea surface temperature (SST) bias. As one of the factors determining the SST bias, the asymmetry of tropical net surface heat flux in Atmospheric Model Intercomparison Project (AMIP) simulations is identified as a skillful predictor of the PAI change from an AMIP to a coupled simulation, with an intermodel correlation of 0.90. Using tropical top-of-atmosphere (TOA) fluxes, the correlations are lower but still strong. However, the extratropical asymmetries of surface and TOA fluxes in AMIP simulations cannot serve as useful predictors of the PAI change. This study suggests that the largest source of the DI bias is from the tropics and from atmospheric models.

1. Introduction

The double Intertropical Convergence Zone (ITCZ) (DI) problem characterized by excessive precipitation in the southern tropics is a long-standing problem in climate models [*de Szoeke and Xie*, 2008; *Lin*, 2007; *Mechoso et al.*, 1995]. Understanding the formation of DI remains a challenge as it is potentially related to deficiencies in individual model component as well as various feedback. Compensating errors can also make it difficult to isolate individual error sources. Many hypotheses have been proposed to explain DI formation. Among them, convection parameterization has been argued to be one of the key bias sources. For example, models with lower deep convection threshold typically have more severe DI [*Bellucci et al.*, 2010; *Oueslati and Bellon*, 2015]; convection closure [*Zhang and Wang*, 2006] and lateral entrainment [*Hirota et al.*, 2011] are also critical factors determining DI formation. From the ocean point of view, the underestimated coastal wind stress and overestimated incoming shortwave forcings in the southeast Pacific/Atlantic have been underlined to contribute to the formation of DI through changing local sea surface temperature (SST) [e.g., *Ma et al.*, 1996; *Richter*, 2015]. The misrepresentation of coupled ocean-atmosphere feedback may also play an essential role in shaping the tropical SST pattern as well as the DI [*Lin*, 2007].

The aforementioned studies tend to imply that the DI problem originates from the tropics. By contrast, some recent studies have argued that the DI problem is in large part driven by the extratropical biases associated with underestimated cloud cover in the Southern Ocean [*Hwang and Frierson*, 2013; *Li and Xie*, 2013]. Many models produce fewer than observed clouds and consequently excessive incoming shortwave in the Southern Ocean [*Hwang and Frierson*, 2013; *Trenberth and Fasullo*, 2010]. This extratropical bias is expected to excite northward atmospheric energy transport across the equator that necessitates enhanced (suppressed) convection to the south (north) of the equator [*Hwang and Frierson*, 2013]. This hypothesis suggests that the ITCZ tends to shift to the warmer hemisphere [*Broccoli et al.*, 2006; *Kang et al.*, 2008]. However, several recent studies with fully coupled models [*Deser et al.*, 2014; *Hawcroft et al.*, 2016; *Kay et al.*, 2016; *Tomas et al.*, 2016] have pointed out that the mean ITCZ location need not shift to the warmer hemisphere with the extratropical perturbations, to the extent that the resulting change in energy transport occurs mainly in the ocean rather than in the atmosphere. The other possibility is that the effect from Southern Ocean radiation bias on the tropical precipitation bias can be compensated by the radiation bias in other latitude bands [*Adam et al.*, 2016; *Kay et al.*, 2016].

Realizing the difficulty in determining the causality in a coupled system given various feedback and error compensations, the focus of this study is on the question of whether and how one can best predict the DI bias of a coupled model from the Atmospheric Model Intercomparison Project (AMIP) simulation with the atmospheric component of the coupled model (i.e., simulation with SST prescribed at observed values). If one can predict the coupled model bias reasonably well, this has direct implication for model development and bias reduction strategies. But also, by comparing tropical versus extratropical AMIP predictors of the coupled DI bias, this approach provides insight onto the question of how the ITCZ position is controlled.

2. Data and Methodology

Several observational data sets are used in this study, comprising (1) precipitation from the Global Precipitation Climatology Project (GPCP) v2.2 [*Adler et al.*, 2003], (2) SST and turbulent heat flux from the European Centre for Medium-Range Weather Forecasts Interim Reanalysis Data (ERA-Interim) [*Dee et al.*, 2011], and (3) radiation fluxes from Clouds and the Earth's Radiant Energy System (CERES, v2.8) [*Wielicki et al.*, 1996]. Nineteen Coupled Model Intercomparison Project phase 5 (CMIP5) models are used that have both AMIP simulations and corresponding coupled historical simulations [*Taylor et al.*, 2011] (Table S1 in the supporting information). We use the time period of 1979–2005 for our analysis.

The definition of DI varies among different studies. Some use the mean precipitation over the southeast tropical Pacific (150°W–100°W, 20°S–0) [*Bellucci et al.*, 2010; *Oueslati and Bellon*, 2015], while others use a hemispheric precipitation asymmetry index (PAI) computed by differencing the precipitation over the northern (0–360°E, 0–20°N) and southern (0–360°E, 0–20°S) tropics normalized by their tropical mean (0–360°E, 20°S–20°N) [*Hwang and Frierson*, 2013]. Here we use the PAI definition following *Hwang and Frierson* [2013] as the DI problem is not only evident in the Pacific but also evident in the Atlantic basin (Figure 1).

Assuming that the models are independent, the threshold of a significant correlation stands at 0.46 for 19 models at the 95% confidence level based on the Student's *t* test.

3. Results

3.1. The DI Problem in CMIP5 Models

Compared to GPCP precipitation, the mean of Multi-Model Ensemble (MME) of 19 CMIP5 AMIP simulations has a bias with excessive precipitation over the tropical oceans and underestimated precipitation over East Asian monsoon region, central North America, and Amazon (Figure 1a). Figure 1b shows the coupled simulations with a similar but more severe precipitation bias over tropical oceans than the AMIP simulations. The difference between the coupled and AMIP simulations is shown to manifest as suppressed precipitation over north Indian Ocean, western North Atlantic including Caribbean Sea, and increased precipitation over the southeast Pacific/Atlantic, indicating an overall southward shift of the mean ITCZ (Figure 1c). This southward shift of mean precipitation is more evident from the annual and zonal mean results (Figure 1d). Another interesting feature is that the DI problem mainly takes place over the ocean domains rather than over the land regions.

Compared to GPCP, 11 out of the 19 AMIP simulations have too positive PAI, implying too much precipitation in the northern tropics than observed (Figure 1e). By contrast, for the coupled simulations only five models have comparable PAI with observations and the others exhibit dramatically decreased PAI. Six models even have negative PAI, implying that the mean ITCZ shifts to the south of the equator (Figure 1e). The MME mean of 19 AMIP simulations has a PAI of 0.22 comparable to observations (0.20), but the MME mean of 19 coupled simulations has a substantially decreased value of 0.04 (Figure 1e). Therefore, it is concluded that a large portion of tropical precipitation bias in coupled models originates from the SST biases generated by interaction with the ocean. The intermodel correlation of PAI between AMIP and coupled simulations is −0.18, suggesting that the PAI in AMIP simulations is not in itself a good predictor of the PAI in the corresponding coupled models. In particular, a model with realistic AMIP precipitation simulation cannot guarantee a realistic coupled model precipitation performance.

What gives rise to the southward shift of mean ITCZ in coupled simulations compared to their AMIP simulations? From an point of view of the atmosphere, the bias source can be traced back to boundary SST, the

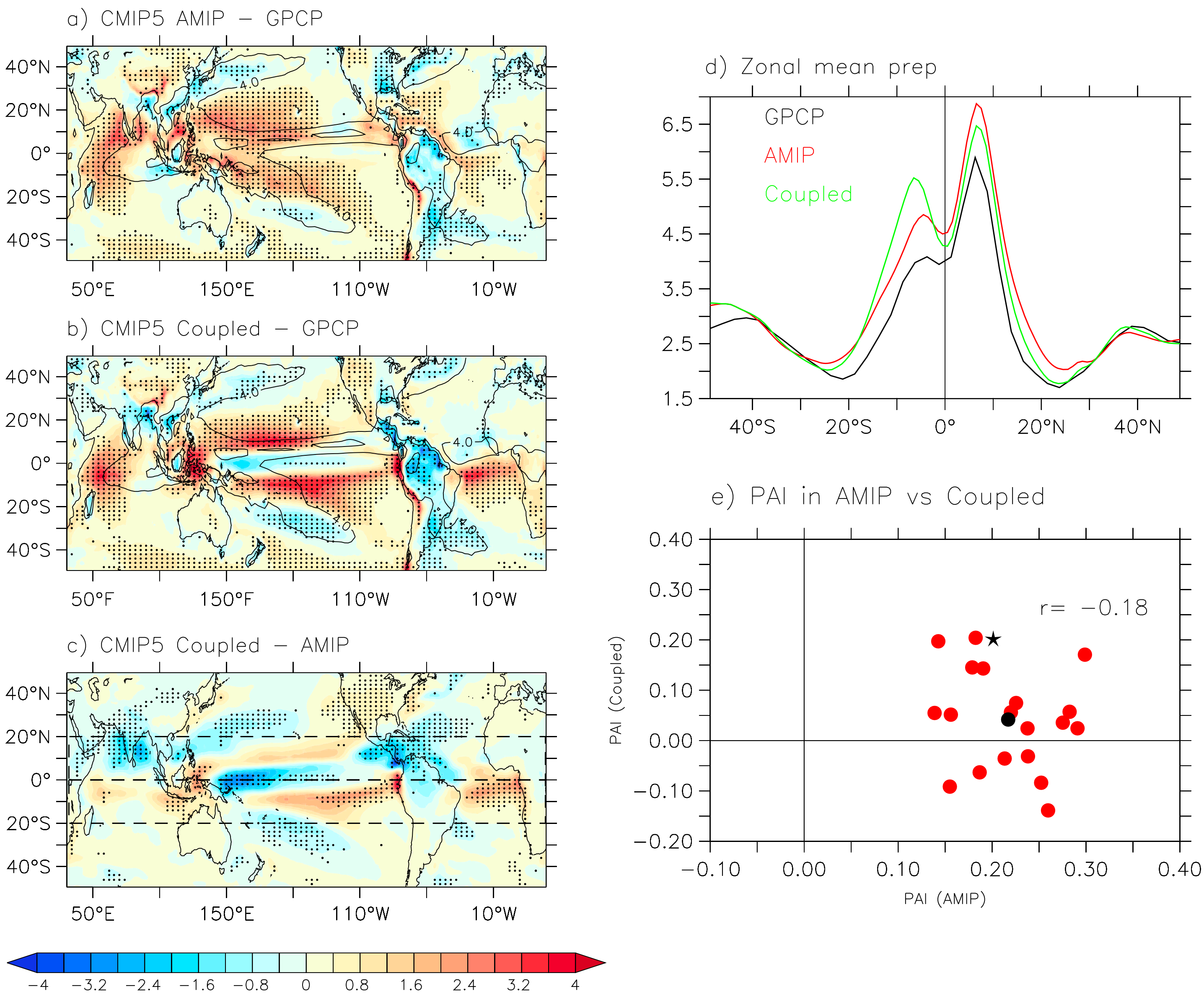

Figure 1. Annual mean precipitation bias (mm/d) from Multi-Model Ensemble (MME) mean of 19 CMIP5 model for their (a) AMIP and (b) historical coupled simulations compared with GPCP. Contours in Figures 1a and 1b are the observational precipitation. (c) Difference between historical and AMIP simulations. Stippling denotes regions where more than 15 of the 19 models have the same sign as the MME mean. (d) Zonal and annual mean precipitation from GPCP (black), the MME mean of 19 CMIP5 AMIP (red), and coupled (green) simulations. (e) Scatter diagram of precipitation asymmetric index (PAI) between AMIP simulations and coupled simulations (red dots) and their MME mean (black dot). The observational PAI is 0.20 (black star). The PAI is calculated by using the precipitation difference between (0–20°N, 0–360°E) and (0–20°S, 0–360°E) normalized by tropical mean. All data used here are from 1979 to 2005.

influence of which might be understood by emphasizing the surface flux or the top-of-atmosphere (TOA) radiation. The SST bias from the MME mean of 19 CMIP5 coupled simulations is characterized by a strong hemispheric asymmetry, while the tropical asymmetry (−0.46°C, 0–20°N minus 0–20°S) is weaker than that over the extratropics (−1.1°C, 20°N–70°N minus 20°S–70°S) (Figure 2a). However, the PAI change (from AMIP to coupled simulations) is more significantly correlated with the meridional asymmetry of tropical SST bias than the extratropical SST bias (with an intermodel correlation of 0.89 versus 0.29) (Figures 2b and 2c). The intermodel comparison offers statistical evidence that the tropical SST bias is critical to explain the southward shift of ITCZ in coupled models. This is consistent with previous studies [*Hwang and Frierson*, 2013; *Li and Xie*, 2013].

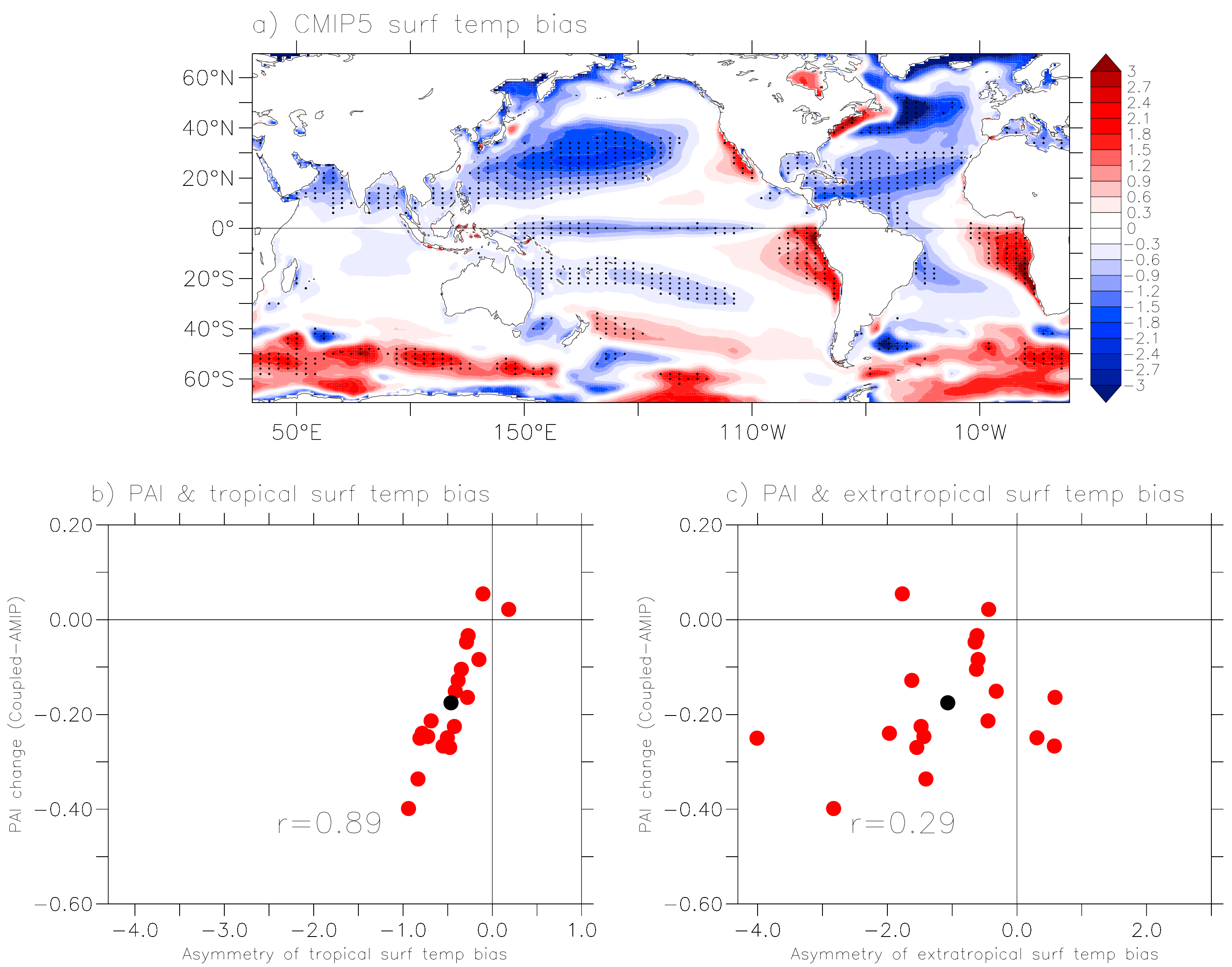

Figure 2. (a) Annual mean SST bias from the MME mean of 19 CMIP5 coupled models. Stippling denotes regions where more than 15 of the 19 models have the same sign as the MME mean. (b) The scatter diagram between the asymmetry of tropical SST bias (0–20°N minus 0–20°S) and PAI change (from AMIP to coupled simulations). (c) Similar to Figure 2b but the *x* axis is for the asymmetry of extratropical SST bias (20°N–70°N minus 20°S–70°S). The MME mean of 19 CMIP5 simulations is denoted by black dots in Figures 2b and 2c.

3.2. Prediction of PAI From AMIP Simulations

The importance of tropical SST bias in the DI formation raises the question as to what determines the coupled model SST bias over the tropics. Is the DI problem predictable based on AMIP simulations? Here the PAI change from AMIP to coupled simulations is used as a predictand. Both surface heat flux and TOA radiation are strongly tied to SST which is different among different coupled simulations. For example, changes of SST directly influence surface latent heat flux via altering specific humidity, and also radiative fluxes at surface and TOA through enhancing/suppressing convection. Consequently, examination of surface heat flux and TOA radiation in coupled simulations in isolation cannot easily isolate the underlying causality. Therefore, we investigate the corresponding AMIP simulations that share the same atmospheric models with 19 CMIP5 coupled simulations to predict the SST and precipitation in the coupled models.

From the ocean point of view, surface heat flux is one of the most important sources contributing to SST biases [e.g., *Richter*, 2015], but this surface flux is not precisely constrained from observations. Taken

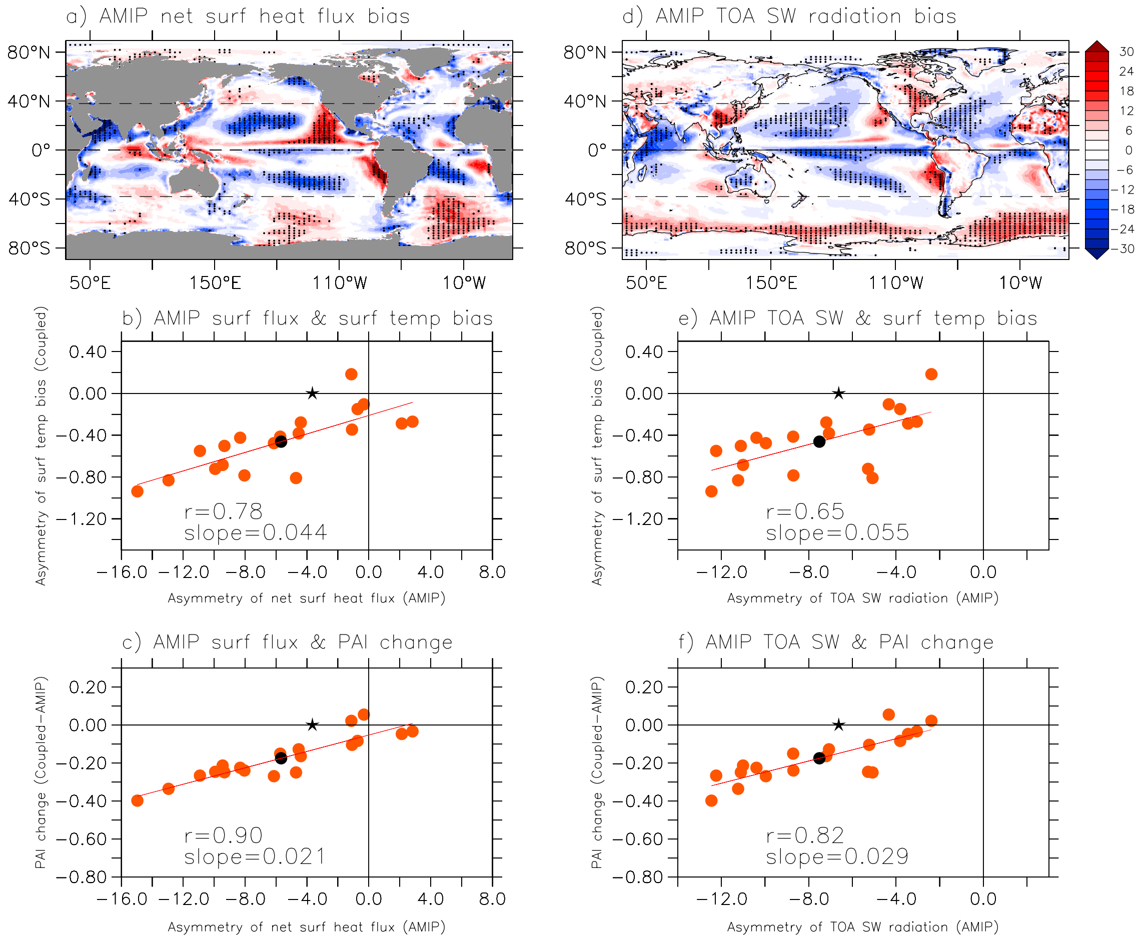

Figure 3. (a) The net surface heat flux bias (W/m^2, positive downward) from the MME mean of 19 CMIP5 AMIP simulations. Stippling denotes regions where more than 15 of the 19 models have the same sign as the MME mean. (b) The scatter of the meridional asymmetry of zonal mean net surface heat flux bias from AMIP simulations versus the meridional asymmetry of zonal mean SST bias in coupled models ($r = 0.78$). (c) Similar to Figure 3b but the x axis is for the meridional asymmetry of zonal mean net surface heat flux ($r = 0.90$). The right plot is similar but for the net TOA shortwave radiation. The asymmetry of surface heat flux and TOA shortwave radiation is calculated based on the contrast between 0–38°N and 0–38°S, while the asymmetry of SST bias and PAI is defined as the contrast between 0–20°N and 0–20°S. The black dots denote the MME mean of 19 models, and the red lines show the linear regressions. The black stars represent the observational values. Note that only the values over the oceans are used when computing the surface heat flux.

separately, the CERES surface radiation data and ERA-Interim turbulent flux are thought to be relatively reliable compared to other sources of surface flux data, but they are not energetically consistent in the sense that the global mean net surface flux is a very unrealistic 9.3 W/m^2. We have removed the global mean value for this analysis, which we hope is justifiable given that our focus here is on understanding north-south asymmetries in the SST bias and precipitation patterns. Meanwhile, the choice of observational data sets does not affect intermodel correlations.

The net surface heat flux from the MME mean of AMIP simulations (Figure 3a) features a bias pattern similar to that of the coupled model SST bias over the tropics (Figure 2a), lending support to the assertion that the coupled model SST bias is partly from the surface heat flux bias. As a measure of the interhemispheric asymmetry of the heat flux bias pattern, for this figure we use the difference between the 0–38°N and 0–38°S averages. We will return to the sensitivity of these results to the region chosen for this purpose in the following. For the 19 CMIP5 models, the meridional asymmetry of net surface heat flux in AMIP simulations has significant correlation with the meridional asymmetry of SST bias in coupled models ($r = 0.78$; Figure 3b) as well as the PAI change ($r = 0.90$; Figure 3c). Thus, roughly 80% of the intermodel variance of PAI change can be explained by the tropical asymmetry of the net surface heat flux in their AMIP simulations even though various ocean models are used in coupled simulations. Compared to the observational value of -3.7 W/m^2,

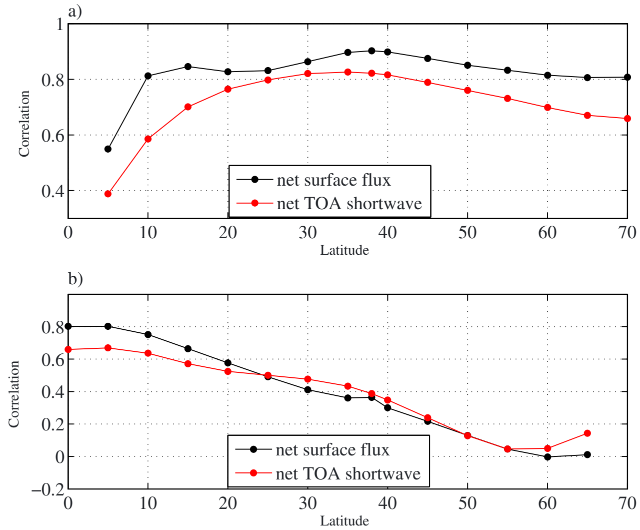

Figure 4. (a) The correlation coefficient between the asymmetry of net surface heat flux (red) (TOA net shortwave radiation, black) from AMIP simulations, and the PAI change from AMIP to coupled simulations. The *x* axis is the latitude at which the asymmetry of TOA radiation and net surface heat flux is defined, such that, for example, the latitude 40 refers to the contrast between 0–40°N and 0–40°S. (b) Similar to Figure 4a but with the asymmetry defined starting from a fixed high-latitude boundary at 70°, with the latitude 40, for example, referring to the contrast between 70°N–40°N and 70°S–40°S.

the meridional asymmetry of net surface heat flux in 19 AMIP simulations displays large spread from −15.2 to 2.8 W/m^2, and 13 out of the 19 models have overestimated meridional asymmetry of net surface heat flux, with more energy input into the southern tropics than into the northern tropics (Figure 3b). This is consistent with the relative warmth of the southern tropics compared to the northern tropics (Figure 2a) and the southward displacement of the ITCZ (Figure 1c).

Investigation of individual heat flux component shows that both the radiative surface heat flux and latent heat flux biases contribute to the PAI change (Figure S1 in the supporting information). We postulate that the surface heat flux bias in atmospheric models largely determines the asymmetry of SST bias in coupled models, which in turn drives the atmospheric precipitation change. Consequently, the asymmetry of tropical SST and precipitation in coupled simulations can be reasonably predicted by using their AMIP simulations based on simple empirical models:

$$T_{\text{coupled}} = 0.044 \times F_{\text{AMIP}} - 0.29,$$

$$\text{PAI}_{\text{coupled}} - \text{PAI}_{\text{AMIP}} = 0.021 \times F_{\text{AMIP}} - 0.05,$$

where T_{coupled} represents the meridional asymmetry of SST bias (°C) and F_{AMIP} represents the asymmetry of net surface heat flux from AMIP simulations in W/m^2. The slope indicates that a given surface heat flux bias asymmetry (F_{AMIP}) with the magnitude of −10 W/m^2 is expected to produce −0.73°C of SST bias asymmetry (T_{coupled}) and −0.26 change in PAI ($\text{PAI}_{\text{coupled}}$-$\text{PAI}_{\text{AMIP}}$). The significance of this prediction of the PAI in coupled models from the PAI in AMIP models has been tested using cross validation [*Michaelsen*, 1987] (Figure S2).

Note that here we use ocean-only data for surface heat flux and surface temperature (SST). The net surface heat flux over land is nearly zero and cannot serve as a predictor of the PAI. In addition, we find that the meridional asymmetry of tropical SST bias is more highly correlated with the PAI change than the asymmetry of tropical surface temperature bias including both land and ocean (r = 0.89 versus 0.83), consistent with the fact that the DI problem is mainly located over the ocean domains (Figure 1).

The surface heat flux bias may partly originate from the TOA radiation biases. We have also attempted to use net TOA shortwave radiation to predict the PAI change, because the atmosphere is fairly transparent to shortwave radiation and the SST can thereby be directly altered. The TOA shortwave radiation bias from the MME mean of 19 AMIP simulations resembles the pattern in the net surface heat flux bias over the tropics (Figure 3d versus Figure 3a). Across 19 models, the tropical meridional asymmetry of net TOA shortwave radiation in AMIP simulations is significantly correlated with the tropical asymmetry of SST bias (r = 0.65; Figure 3e) and also the PAI change (r = 0.82; Figure 3f). The TOA longwave radiation has a similar (but opposite sign) bias pattern, but its relationship with PAI is likely to be simply due to the anticorrelation between the patterns of shortwave and longwave TOA fluxes in the tropics, so the longwave bias is unlikely to provide additional predictive power over the shortwave flux alone (Figures S3c and S3f). We interpret these results as supporting the picture that the DI problem in coupled simulations is partly attributable to the TOA shortwave radiation bias in their AMIP simulations, and the TOA shortwave radiation predictor has a significant correlation with the net surface heat flux predictor ($r = 0.87$).

We present, in Figure 4, the sensitivity of the skill in prediction of the coupled-minus-AMIP PAI to the choice of the latitude bands in defining the predictors. The predictors are first defined as the interhemispheric contrasts of net surface heat flux or net TOA shortwave radiation between [0–ϴ°] and [−ϴ°–0], where we examine choices of the bounding latitude ϴ° ranging from 5° to 70° (Figure 4a). Significant correlations are obtained for ϴ° starting from latitude 10° with the highest correlations at latitude 35°–38°, and then the correlations decrease along with further increase of ϴ°. A correlation coefficient of 0.46 represents a threshold at the 95% confidence level. By contrast, if the predictors are defined starting from the extratropics, that is, using (70°N–ϴ°) and (70°S–ϴ°), the correlations generally increase gradually along with the decrease of the latitude ϴ° (Figure 4b), with insignificant values until the averaging region penetrates into the subtropics. The extratropical surface heat flux and TOA shortwave radiation cannot be used to predict the DI reliably, hinting that the extratropical biases may not be the key for the DI formation in this set of models. These results strongly suggest that the severity of the DI problem in coupled models, as measured by the PAI, is highly predictable from AMIP simulations, and the majority of the bias sources are from the tropics and from atmospheric models.

It is of interest to note that the regression lines in Figure 3 do not pass through the observations. This suggests that the PAI will be biased even with perfect surface heat flux and TOA shortwave radiation as measured by these simple measures of interhemispheric asymmetry. One has to be cautious when comparing with surface heat flux observations, but the more reliable TOA observations present a consistent picture. This may represent a way of isolating the potential contributions either from atmospheric biases not adequately quantified by these measures of interhemispehric asymmetry, from biases in ocean models as well as from biases in coupled atmosphere-ocean feedback.

4. Summary and Discussion

The spurious double ITCZ (DI) problem is a persistent bias in coupled climate models but with many different opinions regarding its source. Motivated by the fact that the intermodel PAI change from AMIP to coupled simulations is highly correlated with the asymmetry of the tropical SST bias, this study attempts to predict the precipitation asymmetry index (PAI—a measure of the severity of the tropics-wide DI bias) in coupled model from AMIP simulations. It is revealed that the PAI change from AMIP to coupled simulations can be reasonably predicted by the tropical asymmetry of net surface heat flux in the AMIP simulations ($r = 0.90$), which in turn is partly originating from the TOA shortwave radiation bias. However, the high-latitude biases, both net surface heat flux and net TOA shortwave radiation in AMIP simulations, do not provide a skillful prediction of the severity of DI problem in coupled models. The quality of the prediction of the DI bias in the CMIP5 models from the corresponding AMIP simulations indicates that the coupled model bias can be understood from atmospheric biases in simulations without SST feedback. This is valuable for climate model development, emphasizing the importance of focusing on the tropics for model development.

Even though the19 CMIP5 models are not fully independent, making it difficult to estimate a true significance, we note that approximately 80% of the intermodel variance can be explained by the net surface heat flux in their AMIP simulations. This implies that the majority of bias sources are likely from the tropics and from atmospheric models. The extratropical biases (surface heat flux and TOA shortwave radiation) are secondary for the DI formation, although we cannot completely rule out its contribution. The relative contribution of the Southern Ocean radiation bias and tropical radiation bias on the DI problem will be explored in a future study by using coupled model sensitivity experiments. Ocean model biases, such as the weaker than observed coastal upwelling and unrealistic representation of ocean eddies [e.g., *Richter*, 2015], also potentially influences the DI problem. More systematic studies are required to detail the contribution of the various processes/feedback and model components involved in changing mean SST, and more reliable observational surface heat flux and atmospheric state data are also desirable to better understand the model deficiencies.

This study is generally consistent with other studies shedding light on the importance of cross-equatorial energy transport in determining the ITCZ location [e.g., *Hwang and Frierson*, 2013; *Adam et al.*, 2016; *Bischoff and Schneider*, 2014] as the asymmetry of SST biases tend to drive an anomalous Hadley circulation responsible for the energy transport from one hemisphere to the other hemisphere. Meanwhile, the CMIP5 models also exhibit pronounced symmetric component of tropical precipitation bias that is likely linked to the bias of net energy input to the atmosphere over the equatorial region [*Adam et al.*, 2016; *Bischoff and Schneider*, 2014]. Further research is desired to unravel whether the symmetric component of tropical precipitation bias in coupled models can be predicted from their corresponding AMIP simulations.

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