Disentangling the effect of regional SST bias on the double-ITCZ problem

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Abstract

This study investigates the causes of the double intertropical convergence zone (ITCZ) bias by disentangling the individual contribution of regional sea surface temperature (SST) biases. We show that a previously suggested Southern Ocean warm bias effect in displacing the zonal-mean ITCZ southward is diminished by the southern midlatitude cold bias effect. The northern extratropical cold bias turns out to be most responsible for a southward-displaced zonal-mean precipitation, but the zonal-mean diagnostics poorly represent the spatial pattern of the tropical Pacific response. Examination of longitude-latitude structure indicates that the overall spatial pattern of tropical precipitation bias is largely shaped by the local SST bias. The southeastern tropical Pacific wet bias is driven by warm bias along the west coast of South America with negligible influence from the Southern Ocean warm bias. While our model experiments are idealized with ocean dynamics being absent, the results shed light on where preferential foci should be applied in model development to improve the certain features of tropical precipitation bias.

1. Introduction

Climate models’ fidelity in projecting the future climate relies on their ability to accurately simulate the mean climate state (Shukla et al. 2006). Most climate models continue to have difficulty since the early days of model development in reproducing precipitation distributions at regional scales, thus impairing the fidelity of their future projections. Most notably, the so-called double-intertropical convergence zone (ITCZ) phenomenon involves a complex spatial structure in the tropics, and hence it can hardly be described as a single aspect.

In the zonal-mean perspective, the precipitation bias can be decomposed into the hemispherically symmetric and anti-symmetric components (Adam et al. 2016; Kim et al. 2021). The symmetric component is characterized by excessive precipitation off the equator and deficient equatorial precipitation (Lin 2007), linked to the biases in net energy input (NEI) to the atmospheric column in the equatorial region (Adam et al. 2016; Bischoff and Schneider 2016), particularly owing to the erroneous ocean heat uptake associated with the equatorial upwelling (Kim et al. 2021). By contrast, the anti-symmetric component displays a precipitation deficit to the north and an excess to the south of the equator (Li and Xie 2014), linked to the hemispherically asymmetric biases in the atmospheric column energy via so-called the energetics framework (e.g., Kang et al. 2008). The hemispheric asymmetry of top-of-atmosphere radiation bias in the extratropics is pointed out to be the cause of the hemispherically anti-symmetric component of tropical precipitation bias (Adam et al. 2016). In particular, too much energy flux into the atmosphere over the Southern Ocean associated with cloud biases is suggested to cause anomalously northward atmospheric energy transport (AET) across the equator, leading to excessive precipitation in the southern relative to the northern tropics (Hwang and Frierson 2013). While some fully coupled model studies indicate that the radiation bias correction over the Southern Ocean leads to only a limited improvement of the double ITCZ bias owing to the compensating effect of a dynamic ocean (Hawcroft et al. 2017; Kay et al. 2016; Xiang et al. 2018), other fully coupled model studies report a significantly alleviated double ITCZ bias through the improvement in the Southern Ocean radiation bias
(Mechoso et al. 2016; Kawai et al. 2021). A multi-model study shows that radiative cooling over the Southern Ocean robustly shifts the tropical precipitation northward, albeit with a substantial model spread (Kang et al. 2019). With regard to intermodel uncertainty, the hemispherically anti-symmetric component of double-ITCZ bias is tied to the tropical asymmetry in net surface heat flux estimated from their corresponding Atmospheric Model Intercomparison Project (AMIP) simulations (Xiang et al. 2017).

The zonal-mean characteristics of tropical precipitation bias hide the complex regional structures. The equatorial Pacific shows a precipitation deficit, accompanied by an excessive cold tongue bias, which extends too far west due to an overly strong trade wind (Lin 2007; De Szoeke and Xie 2008). In the meanwhile, the southeastern Pacific (SEP) shows overly strong precipitation (Bellucci et al. 2010; Oueslati and Bellon 2015). The SEP precipitation bias has been linked with a number of factors, including the model-dependent SST threshold required for the onset of deep convection (Bellucci et al. 2010), warm sea surface temperature (SST) biases associated with the underestimated stratus cloud fraction off the coast of Peru (Ma et al. 1996), the smoothing of the Andes orography in climate models (Takahashi and Battisti 2007), and weaker-than-observed alongshore winds (Zheng et al. 2011). Improved simulation of low-level cloud fractions alleviates the SST and rainfall biases in the SEP but exacerbates the equatorial dry and cold tongue biases (Fushan et al. 2005), implying a limited improvement of the overall double-ITCZ bias.

Despite the rich spatial structure of the double-ITCZ bias, previous studies often targeted one single feature, so that the overall bias correction has been limited because improvement in one feature may lead to deterioration of another. As a result, the double-ITCZ problem has been persistent over three Coupled Model Intercomparison Project (CMIP) phases (Mechoso et al. 1995; De Szoeke and Xie 2008; Zhang et al. 2015; Tian and Dong 2020). The double-ITCZ bias imposes a significant barrier to the simulation of the leading mode of tropical Pacific variability, El Niño–Southern Oscillation (Guilyardi et al. 2003; Ham and Kug 2014), and also to model projections of Pacific warming pattern under greenhouse gas increases (Zhou and Xie 2015; Seager et al. 2019). The double-ITCZ bias is also related to equilibrium climate sensitivity, the global mean surface air temperature increase following a CO₂ doubling, which is a measure of the severity of global climate change (Tian 2015).

Identifying the bias sources is a necessary step for improving the simulations of the tropical precipitation distribution. In this study, we systematically design model experiments to identify the contribution of regional SST biases to the specific characteristic of tropical precipitation biases. The tropical precipitation is closely linked to the SSTs (Lindzen and Nigam 1987), which is not solely determined by local mechanisms but also influenced by remote processes. To take into account the impact of the SST biases outside the tropics on the tropical precipitation distribution, we adopt an atmosphere-slab ocean climate model with a prescribed q-flux that replicates the SST bias instead of directly manipulating the SSTs (Kang and Held 2012). The slab ocean configuration instead of the AMIP simulation with prescribed SSTs permits us to evaluate the effect of energetic constraint framework in forming double-ITCZ, and the experiment design is detailed in the next section. This experiment setting offers a unified perspective for interpreting the overall double-ITCZ bias by allowing us to assess the manifestation of regional SST biases in the spatial pattern of tropical precipitation. We provide some
insights into the relative roles played by tropical versus extratropical SST biases in developing the double-ITCZ.

2. Methodology And Experiments

The atmospheric model employed in this study is GFDL AM2.1 (GFDL Global Atmospheric Model Development Team 2004), with 24 vertical levels and a horizontal resolution of 2° latitude × 2.5° longitude. We integrate the AM2.1 with the monthly SSTs prescribed to either the observation (NOAA OI SST V2 data; Reynolds et al. 2002) or those from the historical integration of the corresponding coupled model, GFDL CM2.1 (Delworth et al. 2006), both of which are averaged for the period 1982-2000. The former represents the perfect model without any SST biases while SST biases are present globally in the latter. In all simulations, we prescribe the sea-ice concentration to its monthly climatology averaged between 1982 and 2000 from AMIP2 observational estimates supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The prescribed SST experiments are integrated for 50 years, and the first 10 years are discarded as a spin-up. Figure 1a illustrates the climatological SST bias of CM2.1, the difference from the observed NOAA SST data. Three features stand out: 1) prominent cold bias in the northern extratropics, 2) zonally elongated cold and warm biases in the Southern subtropics and the Southern Ocean, respectively, and 3) tropical-wide cold bias with a strip of warm bias in the eastern ocean basins near the coast. These features are robust, shared by two-thirds of CMIP5/6 models (stippling in Fig. 1a), as noted in previous literature (e.g., Wang et al. 2014; Xiang et al. 2017). The global SST bias of CM2.1 (Figure 1a) and that of the multi-model mean of CMIP5/6 models (Figures S1a and S1b) are strongly correlated at 0.99. This suggests that the SST bias pattern from CM2.1 is representative of that from the current generation of global climate models.

We intend to disentangle the effect of these regional SST biases on the tropical precipitation. For this purpose, we obtain the q-flux that aims to reproduce the climatological SST pattern from either the observation or the model CM2.1. Specifically, the q-flux is calculated as the monthly climatology of net surface heat flux in the aforementioned prescribed SST simulations. The q-flux that reproduces the observed SST is denoted as Q_{OBS} and that reproducing the model SST as Q_{MODEL}. The difference between Q_{MODEL} and Q_{OBS} is denoted as Q_{BIAS} (Figure 1b). While our experiment setting does not point to the root cause of Q_{BIAS}, it should ultimately stem from errors in parameterizations of subgrid-scale physics and its interactions with the large-scale flow.

We prescribe the q-flux profiles to the AM2.1 coupled to a 50-m slab ocean that features realistic land-sea distributions and topography. The slab ocean simulation forced by Q_{OBS} represents the perfect model climate with no SST bias (OBS) while the one forced by Q_{MODEL} represents the model climate with the SST biases around the entire globe (GLO). While the slab ocean simulations do not perfectly reproduce the corresponding fixed SST simulations, it is worth noting that the SST deviations in GLO and OBS from the corresponding prescribed SST simulations are similar in spatial pattern and magnitude (Figure S2), indicative of common model errors. Consequently, the SST difference between GLO and OBS
(Figure S1c) closely matches the actual SST bias (Figure 1a) and hence the precipitation biases are well reproduced by the slab ocean simulations (contrast Figures 1c and 1d). This confirms that the slab ocean simulations can be used to relate the tropical precipitation bias to the SST bias. In order to disentangle the effect of regional SST bias, we take into account a series of q-flux profiles, formulated as different combinations of $Q_{\text{OBS}}$ and $Q_{\text{MODEL}}$. For example, the slab ocean simulation with $Q_{\text{MODEL}}$ between 20°S and 20°N and $Q_{\text{OBS}}$ over the rest of the globe is intended to examine the effect of tropical SST bias. As details set out in Table 1, we design the experiments to single out the SST bias in the tropics (TRO), the extratropics (EXT), the northern extratropics (EXT-N), and the southern extratropics (EXT-S) divided into equatorward (EXT-SEQ) and poleward (EXT-SPO) of 40°S, as seen in Figure 1b. We divide the southern extratropics relative to 40°S because the SST bias (Figure 1a) and hence q-flux changes sign there (Figures 1b and S3). The sum of the climate response in all regional q-flux simulations closely resembles the climate response in GLO (Figure S4). This near-linearity of the climate responses allows us to adopt the regional q-flux simulations for the attribution of the tropical precipitation biases. All slab ocean experiments are integrated for 30 years after 20 years of spin-up. We regard the slab ocean OBS simulation as the observation and hence the difference from OBS defines the climate bias, denoted by the notation.

To examine the large-scale energetics control on the double-ITCZ bias, we calculate the net energy input to the atmospheric column over the equatorial region between 5°S-5°N NEI₀ and the cross-equatorial atmospheric energy transport AET₀. Assuming a negligible energy storage in the annual-mean, NEI is calculated as the sum of downward net radiative fluxes at the top-of-atmosphere and upward net heat fluxes at the surface. We calculate AET₀ by integrating NEI over the Southern Hemisphere (SH) and Northern Hemisphere (NH) and dividing the difference between the two in half.

3. Results

3.1. Tropical vs extratropical contribution

In the zonal-mean, the double-ITCZ bias can be divided into the hemispherically symmetric (i.e., the excessive precipitation off the equator and underestimated equatorial precipitation) and anti-symmetric (i.e., more precipitation to the south than north of the equator) components. We respectively measure the degree of change in each component using the equatorial precipitation index ($\gamma$), defined as the equatorial (2°S-2°N) precipitation divided by the tropical mean (20°S-20°N) subtracted from unity (Adam et al. 2016), and the precipitation centroid ($\lambda$), defined as the centroid latitude that renders an equal area-integrated precipitation from 20°S to 20°N (Frierson and Hwang 2012).

The CM2.1 presents deficient equatorial and excessive off-equatorial precipitation bias, with which is closely reproduced in GLO where (Figures 2f and 3a). The bias amounts to in TRO and in EXT, suggestive of the tropical origin of the hemispherically symmetric bias, consistent with Adam et al. (2016). A large negative bias in TRO is due to the negative equatorial $Q_{\text{BIAS}}$ by design (Figures 1b and S3) since the symmetric component is related to NEI₀ (Figure 3a). It is of interest to note...
that the bias is significant and positive in EXT despite zero equatorial $Q_{\text{BIAS}}$ therein, as the southern extratropical warm response extends into the southeastern tropical Pacific (Figure 2b; see section 3.3 for details).

The hemispherically anti-symmetric component of in CM2.1 is also well reproduced by GLO where, indicative of more precipitation in the southern than the northern tropics (Figure 3b). The bias in GLO is largely driven by EXT wherein while the TRO-induced bias of 0.1 is insignificant. In the GFDL model we consider in this study, $Q_{\text{BIAS}}$ (Figure 1b) presents a strong hemispheric asymmetry in the extratropics (i.e., poleward of 20°) (Figure S3). The north-minus-south $Q_{\text{BIAS}}$ amounts to -0.22 PW poleward of 20° and 0.09 PW equatorward of 20°. More energy input into the southern than the northern hemisphere in EXT results in an anomalously northward cross-equatorial atmospheric energy transport (AET), leading to the southward-displaced tropical precipitation (i.e., negative ; Figure 3b). The dominance of extratropical impact on the hemispherically anti-symmetric component is consistent with Hwang and Frierson (2013) and Li and Xie (2014).

The longitude-latitude structure of the tropical precipitation bias reveals rich spatial patterns imbedded in the zonal-mean (Figures 1c and 1d). The double-ITCZ bias is characterized by the dry bias over the western Pacific (WP), the northward shifted precipitation over the northern ITCZ region (NI), and the zonally elongated wet bias over the southern tropics, covering the SEP and the South Pacific Convergence Zone (SPCZ) regions. The majority of this double-ITCZ bias is reproduced in TRO (Figure 2d) while EXT tends to offset the TRO response only partially (Figure 2e). The pattern correlation with the tropical precipitation bias in GLO (Table 1) clearly indicates that the tropical bias is the key for the formation of overall double ITCZ bias pattern and the extratropical bias is of secondary importance. The tropical SST bias is characterized by an equatorially elongated cold tongue bias, the northern/southern tropical Pacific warm/cold bias, an overall cold bias in the tropical Atlantic, and a narrow strip of strong warm bias along the west of coastlines (Figure 2a). The region of warm bias displays excessive precipitation, and the region of cold bias displays deficient precipitation (Figure 2d). These tropically-induced biases in SST and precipitation, particularly in the Pacific sector, are partially offset by the extratropically-induced biases (Figures 2b and 2e). That is, the extratropical contribution acts to mitigate the locally driven biases, except over SEP where the wet bias is induced by the SST biases from both the tropics and extratropics (Figures 2d and 2e). Relatively, the warm bias off the Peruvian coast is evident in both TRO and EXT (Figures 2a and 2b). Thus, the extratropical SST bias correction may reduce the SEP wet bias while worsening the precipitation bias over the other tropical regions.

### 3.2. Contrasting the effect of zonally symmetric and asymmetric components of tropical bias

In the previous section, we show that the spatial structure of double-ITCZ is due in large part to the tropical SST bias. Noting that the tropical bias features a widespread cold bias (Figure 2a), we decompose the tropical $Q_{\text{BIAS}}$ into the zonal average and the deviation from the zonal average. The experiment forced by the zonally uniform $Q_{\text{BIAS}}$ in the tropics is denoted as [TRO] and that forced by the zonally asymmetric component as TRO* (Figure 4a-c). Although the amplitude of regional q-flux in [TRO]
amounts to only a quarter of that in TRO* (Figure 4a,b), the zonal-mean biases in SST and precipitation are mostly caused by [TRO] (Figure 4f,i). Free of zonal-mean q-flux, TRO* results in nearly zero AET₀ and NEI₀ (Figure 3) and thus has little impact on the zonal-mean precipitation bias (Figure 4i).

The q-flux in [TRO] is directed downward in the deep tropics within ~5° latitude (Figure 4a). Hence, NEI₀ is negative, resulting in an equatorial dry bias, that is, (Figures 3a and 4i), consistent with Adam et al. (2016). This equatorial surface flux bias is likely to originate from errors in cloud fraction over the equatorial Pacific (Li and Xie 2012; Wittenberg et al. 2006) and erroneous representation of equatorial upwelling, which may originate from either extratropical SST biases or upper-ocean mixing parameterization (Burls et al. 2017; Moum et al. 2013). Anomalously downward q-flux leads to the tropical-wide cold SST bias (Figure 4d). Despite the zonally uniform q-flux in [TRO], the resulting tropical SST bias is more pronounced in the eastern than the western Pacific basin. This zonal asymmetry in the tropical Pacific SST response in [TRO] results from the contrasting SST-surface shortwave flux feedback (Lin 2007) and the evaporative damping rate (Xie et al. 2010) over the warm pool and the cold tongue. Reduced SSTs over the western Pacific inhibit deep convection and the resulting reduction in clouds allows for more surface downward shortwave radiation. On the contrary, reduced SSTs over the eastern Pacific increase the static stability in the boundary layer, increasing the low cloud amount (Klein and Hartmann 1993), which in turn decreases the surface downward shortwave radiation. The negative SST-surface shortwave flux feedback over the western Pacific mutes the SST response while the positive SST-surface shortwave flux feedback over the eastern Pacific amplifies the SST response (contours in Figure 4d). In addition, a climatologically weaker evaporation is associated with a smaller evaporative damping rate so that the SST response to a zonally uniform q-flux is locally enhanced over the climatologically-colder eastern than the climatologically-warmer western equatorial Pacific. A consequently enhanced trade easterlies give rise to anomalous equatorial divergence, reducing precipitation over the warm pool while shifting the northern ITCZ northward and the SPCZ southward (Figure 4g).

Despite a small zonal-mean response in TRO* (Figure 4f,i), the regional precipitation responses are as large as that in [TRO] (compare Figures 4g and 4h). While an overall tropical cooling is associated with the zonally uniform Q_BIAS (Figure 4d), the warm biases over the northern tropical Pacific and the west coast of America and Africa are associated with the zonally asymmetric Q_BIAS (Figure 4e). The northern tropical warm bias, which is partially attributable to the low biased orography over Central America in climate models (Baldwin et al. 2021), drives a strong wet bias over the NI region (Figure 4h). By contrast, the low biased Andes orography is suggested to be partly responsible for the warm SEP bias (Takahashi and Battisti 2007). This warm bias off the west coast of South America is concentrated in a narrow strip (Figure 4e) but induces a large-scale convergence to create the wet bias extending from the Peruvian coast to the SEP region (Figure 4h). The dry bias over the western Pacific in TRO* is associated with the relative cooling over the warm pool. Thus, TRO* is equally important as [TRO] for shaping the regional precipitation pattern bias (Figure 4g,h) despite the negligible zonal-mean precipitation bias with nearly zero and (Figure 3). In fact, the pattern correlation with the GLO response is slightly larger in TRO* than in [TRO] (Table 1).
3.3 Decomposition of extratropical contribution

We show in section 3.1 that the tropical surface flux biases are most responsible for developing an overall double-ITCZ bias but the hemispherically anti-symmetric component of zonal-mean precipitation bias is in large part driven by the extratropical biases. Hwang and Frierson (2013) suggest that the typically underestimated cloud cover in the Southern Ocean makes the SH warmer than the NH, inducing an anomalous Hadley cell that drives a northward AET₀, which then leads to excessive precipitation to the south of the equator. Indeed, the top-of-atmosphere shortwave cloud radiative effects (SWCRE) are biased high poleward of 50°S but is flanked by low biases on the equatorward side in multiple atmosphere-only models participating in the Fifth and Sixth phase of AMIP5/6 (Figures S5). This reflects that the SH high-latitude warm bias and the SH mid-latitude cold bias in CMIP5/6 models (Figures S1a and S1b) partly originate from the erroneous representation of atmospheric processes. The GFDL CM2.1 shows the same tendency of warm biases poleward of 40°S flanked by cold biases on the equatorward side (Figures 1a), which is also evident in the previous version of the model CM2.0 (Delworth et al. 2006). Excessive shortwave absorption poleward of 40°S may be due to insufficient amount of supercooled cloud liquid (Kay et al. 2016), while deficient shortwave absorption on the equatorward side may be due to overly bright tropical low clouds (Nam et al. 2012). That is, the dipole pattern of the Southern Hemisphere SST bias tends to appear as a pair but they seem to result from independent causes.

Given the tendency for the warm and cold biases to co-exist in the southern extratropics, we separate their effects by running the experiments with Qᵦ_BIAS prescribed over either 20°S-40°S (EXT-SEQ) or poleward of 40°S (EXT-SPO). Consistent with the energetics framework, the warm bias poleward of 40°S results in a negative in EXT-SPO while the cold bias over 20°S-40°S results in a positive in EXT-SEQ (Figure 3b). Due to the cancelling effect, the southern extratropical bias as a whole (i.e., poleward of 20°S; EXT-S) has an insignificant impact on the . Although previous literature has emphasized the southern high-latitude warm bias for displacing the zonal-mean ITCZ southward, this study highlights the compensating effect by the neighboring cold bias in the southern mid-latitude.

The negative in EXT-SPO is a manifestation of a southward precipitation shift in all tropical regions except SEP (Figure 5e). It is noteworthy that the southern high-latitude warm bias is not responsible for the SEP wet bias in GLO. Instead, the wet bias over the SI region appears in EXT-SEQ (Figure 5f) associated with a narrow strip of warm bias extending into the Peruvian coast (Figure 5b) associated with the positive Qᵦ_BIAS off Chilean coast (Figure 1b). The separation of EXT-SEQ and EXT-SPO, together with TRO*, clearly demonstrates that the SEP wet bias is driven by the local warm bias due to model errors in regional processes such as underestimated stratus cloud cover (Ma et al. 1996), weak coastal upwelling (Large and Danabasoglu 2006), and/or underrepresented South American orography (Takahashi and Battisti 2007). The northward precipitation shifts in WP and SPCZ in EXT-SEQ are consistent with the energetics framework (Figure 5f). However, the NI region presents a reversed precipitation shift associated with the evident cooling in the northeastern tropical Pacific (Figure 5b). The intensification of north Pacific subtropical high, induced by the propagation of southern extratropical cold bias, results in anomalous northeasterlies over the eastern tropical Pacific, forming a cold temperature
anomaly via the wind-evaporation-SST (WES) feedback and shifting the precipitation equatorward in the NI region. As a result, the southern extratropical bias as a whole is partially responsible for the zonally elongated wet bias south of the equator while alleviating the precipitation biases over the WP and NI regions (contrast Figures 5g and 1c).

Meanwhile, the Northern Hemisphere shows clear cold biases in the extratropics (Figure 1a), which may be related to a weakly simulated Atlantic Meridional Overturning Circulation (Wang et al. 2014), too weak oceanic vertical mixing (Zhu et al. 2020), and/or cloud biases (Figure S5). The experiment with the prescribed $Q_{\text{BIAS}}$ poleward of 20°N (i.e., EXT-N) is to examine the effect of the northern extratropical cold bias in isolation. The anomalously northward AET_0 leads to a southward shift of the tropical precipitation, indicated by a negative $\eta$ (Figure 3b). The northern extratropical cold bias is advected equatorward, but the cooling response is limited to the north of the equator due to the blocking effect by the mean ITCZ (Figure 5d; Kang et al. 2020). A contrast with EXT-S clearly highlights the limited ability of the northern extratropical bias in affecting the SSTs of the opposite hemisphere (Figures 5c vs 5d). The northern extratropical signal in EXT-N penetrates across the equator only through the western Pacific warm pool where deep convection is organized around the equator (Kang et al. 2020). The resulted cold bias around the SH maritime continents acts to shift the SPCZ precipitation northeastward. This is consistent with a southward SPCZ shift in response to the northern extratropical warming in Kang et al. (2019). The northern extratropical cold bias is common to CMIP5/6 models (Figure S1a,b), but it has not been emphasized in the context of double-ITCZ bias. Our experiments raise the possibility of its importance for displacing the overall tropical precipitation southward. Owing to the dipole pattern in the southern extratropical SST biases, the northern extratropical cold bias turns out to be more critical at causing a southward shift of the zonal-mean tropical precipitation (Figures 3b). However, the 2d map of precipitation response shows the tropical Pacific response of comparable magnitude in EXT-S and EXT-N (Figures 5g and 5h). It is the Indian Ocean response of opposite sign that diminishes $\eta$ in EXT-S. A northward precipitation shift over the Indian Ocean in EXT-S, driven by the cold bias over the southern Indian Ocean in EXT-SEQ (Figure 5f), counteracts a southward precipitation shift at other ocean basins.

4. Conclusions

The primary focus of this study is to examine how the regional SST bias is manifest in the double-ITCZ bias. We use one GFDL model, CM2.1, but presume our results to be generally applicable to other models as the global SST and tropical precipitation bias patterns in CM2.1 are largely common to those in current generation of global climate models. The experiment with SSTs prescribed to the observation is first conducted to infer the q-flux that is used to force the slab ocean to replicate the observed SSTs. The same procedure is repeated but with the SSTs prescribed to the model CM2.1. The q-flux difference between the two prescribed SST experiments is denoted as $Q_{\text{BIAS}}$, which reproduces the global SST bias via the slab ocean model. We confirm the linearity of the climate response to the regional $Q_{\text{BIAS}}$, hence, allowing us to decompose biases in the climate system to the contributions from the regional $Q_{\text{BIAS}}$. 
In particular, we single out the effect of the northern extratropical cold bias, the Southern Ocean warm bias, the southern mid-latitude cold bias, and the tropical cold bias. Previous literature raised a possibility of the Southern Ocean warm bias for causing the southward-displaced zonal-mean ITCZ in coupled models. However, the Southern Ocean warm bias effect turns out to be cancelled out by the southern mid-latitude cold bias effect. This pair of opposite-signed extratropical bias in the Southern Hemisphere is quite typical to CMIP5/6 models. Our experiments suggest the northern extratropical cold bias to be responsible for the hemispherically asymmetric bias in the zonal-mean ITCZ.

However, the zonal-mean diagnostics poorly represent the tropical Pacific bias as indicated by an examination of the longitude-latitude structure. For example, the zonally asymmetric tropical bias (i.e., TRO*) has little impact on the zonal-mean tropical precipitation pattern as a result of the cancellation between a large drying response over the equatorial Pacific and a large wetting response over other ocean basins. Hence, the zonally asymmetric tropical bias is as critical as the zonally symmetric tropical bias for shaping the tropical Pacific precipitation bias. Moreover, the hemispherically asymmetric component of the zonal-mean tropical precipitation bias is primarily driven by the extratropical biases, but an overall tropical Pacific bias pattern is largely determined by the tropical biases. A better representation of extratropical processes will lead to only limited improvements to the tropical Pacific bias. In addition, the Southern Ocean warm bias displaces the zonal-mean tropical precipitation southward but has negligible impact on the wet bias over the southeastern Pacific, which turns out to be driven by the narrow strip of warm bias along the west coast of South America. Thus, the zonally averaged precipitation diagnostics have limited implication about local precipitation, hence, caution must be taken when the energetics framework is invoked to understand the regional precipitation response.

Precisely speaking, $Q_{\text{BIAS}}$ is not necessarily the surface heat flux bias itself but encompasses the effect of uncertainties in the subgrid-scale parameterizations on the SST. The origins of regional SST biases are beyond the scope of this study. Major caveat of this study is omission of ocean dynamical feedback, which not only damps the magnitude but also modulates the spatial pattern of tropical climate response to radiative forcing (e.g., Kang et al. 2020). The negative ocean dynamical feedback is shown to be stronger for extratropical than for tropical radiative perturbations (Green et al. 2019; Yu and Pritchard 2019), so that the importance of northern extratropical cold bias in causing the southward-displaced ITCZ may be over-emphasized in our experiments. However, the study provides a useful first-step guidance for where should be targeted to improve certain features of climate biases. A subsequent study with a fully atmosphere-ocean coupled model is warranted to examine how the results reported here are modulated by ocean dynamics.

**Declarations**

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**Conflicts of interest**

The authors declare no competing interests.

**Availability of data and material**

The output from CMIP5 and CMIP6 are provided by the World Climate Research Programme's Working Group on Coupled Modelling and are available at https://esgf-node.llnl.gov/projects/cmip5 and https://esgf-node.llnl.gov/search/cmip6. Model and observational data used in this paper’s analysis is permanently accessible in Zenodo with the identifier https://doi.org/10.5281/zenodo.5062468.

**Code availability**

Not applicable

**Author’s contributions**

Not applicable

**Ethics approval**

Not applicable

**Consent to participate**

Not applicable

**Consent for publication**

Not applicable

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Table
Table 1  Experiment design and the pattern correlation of precipitation response over 20 S-20 N between the individual experiment and GLO.

| Experiment name | Forced latitude | Pattern correlation |
|-----------------|-----------------|---------------------|
| GLO             | 90 S-90 N       | 1.00                |
| TRO             | 20 S-20 N       | 0.97                |
| [TRO]           | 20 S-20 N       | 0.69                |
| TRO*            | 20 S-20 N       | 0.89                |
| EXT             | Poleward of 20  | -0.31               |
| EXT-S           | 20 S-90 S       | -0.13               |
| EXT-N           | 20 N-90 N       | -0.37               |
| EXT-SEQ         | 20 S-40 S       | 0.11                |
| EXT-SPO         | 40 S-90 S       | -0.22               |

Figures

(a) SST bias in CM2.1
(b) QBIAS
(c) Precip bias in CM2.1
(d) δPrecip in GLO
Figure 1

(a) The climatological SST bias in GFDL CM2.1 relative to NOAA OI SST V2 data. Stippling denotes the regions where more than two-thirds of 40 CMIP5 models and 52 CMIP6 models exhibit the same sign of SST bias as in the CM2.1. (b) The difference of net surface heat flux (positive upward) in simulations with the SSTs prescribed to CM2.1 and observation, which is used the q-flux to force the slab ocean model to reproduce the SST bias shown in (a). (c) The climatological tropical precipitation bias in CM2.1, computed as the deviation from Climate Prediction Centre Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997). (d) The difference of precipitation (shading) and surface wind velocity (vectors) between GLO and OBS. The rectangles in (c) and (d) represent the Northern ITCZ (NI), Warm Pool (WP), SPCZ, and Southeastern Pacific (SEP). In (d), the regions are hatched where the response is not statistically different from zero at the 99 % confidence level calculated with a two-sided t-test.

Figure 2

The SST difference between (a) TRO and OBS and (b) EXT and OBS. (d,e) Same as (a,b) but for precipitation and surface wind vector. The zonally averaged difference of (c) SST and (f) precipitation in GLO (black), TRO (red), and EXT (red) from OBS. Hatching in (a,b,d,e) and gray shading in (c,f) indicate where the response is not statistically different from zero at the 99 % confidence level using a two-sided t-test.
Figure 3

Scatter diagram of (a) $\delta NEI_0$ and $\delta E_P$ and (b) $\delta AET_0$ and $\delta p_{cent}$ for all regional q-flux experiments. The correlation coefficients are displayed in the upper right corner of each panel. A horizontal gray solid line indicates the actual CM2.1 precipitation bias relative to CMAP data (Xie and Arkin 1997). The error bars indicate where the response is not statistically different from zero at the 99% confidence level using a two-sided t-test.
**Figure 4**

The (top) q-flux profile, the difference of (middle) SST and (bottom) precipitation and surface wind vector from OBS in (left) [TRO] and (right) TRO*. (c,f,i) The corresponding zonal-mean profiles in [TRO] (solid) and TRO* (dashed). Purple solid (dashed) contours in (d,e) denote a positive (negative) response in shortwave cloud radiative effect at the top-of-atmosphere (positive downward; interval = 4 \( \text{W/m}^2 \)). Hatching in (d,e,g,h) and gray shading in (f,i) indicate where the response is not statistically different from zero at the 99 % confidence level using a two-sided t-test.

**Figure 5**

The difference of (left) SST and (right) precipitation and surface wind vector from OBS in (a,e) EXT-SPO, (b,f) EXT-SEQ, (c,g) EXT-S, and (d,h) EXT-N. Purple solid (dashed) contour lines in (a,b) denote positive (negative) SLP bias with an interval of 5hPa. Hatching indicates where the response is not statistically different from zero at the 99 % confidence level using a two-sided t-test.
Supplementary Files

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