Reduction of Pacific double-ITCZ bias by convection parameterization in NCAR CESM2.2

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Key Points:

- Modifications to the closure in convection parameterization scheme greatly reduce the double-ITCZ bias in all seasons in CESM2.2
- Convection scheme can modulate the tropical atmosphere-ocean feedback processes, through which it influences the SST and double-ITCZ biases
- Surface heat flux changes play a limited role in reducing the SST and double-ITCZ biases

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Abstract

The impact of convective closure on the double-ITCZ bias in the NCAR CESM2.2 is investigated in this study. The standard CESM2.2 simulates a remarkable double-ITCZ bias in the central and eastern Pacific, especially in boreal winter and spring. Modifications to the closure in convection parameterization scheme greatly reduce the double-ITCZ bias in all seasons, demonstrating that convection parameterization can substantially influence the double-ITCZ bias in CESM2.2. Further analyses suggest that convection parameterization can modulate the tropical atmosphere-ocean feedback processes, through which it influences the SST in the southern ITCZ region and hence the double-ITCZ bias. The changes in the upper ocean temperature advection induced by modified convective closure plays important roles in reducing the warm SST bias and double-ITCZ precipitation bias in the southern ITCZ region. The modified convective closure improves the low-level cloud and shortwave cloud radiative forcing in the southeastern Pacific. However, surface heat flux plays only a limited role in reducing warm SST bias and double ITCZ bias because the impacts of shortwave radiation changes are largely canceled by changes in longwave radiation and latent heat flux.

Plain language summary

Despite decades of model development, the large-scale distribution of precipitation simulated by most of coupled global climate models (GCMs) still displays a remarkable double-intertropical convergence zone (ITCZ) bias over the tropical Pacific Ocean. Observations show asymmetrical distribution of precipitation with respect to the equator in the central and eastern Pacific with one intense ITCZ precipitation band north of the equator all year-round and a much weaker zonal rain band south of the equator (southern ITCZ) only in boreal spring. However, coupled GCMs tend to simulate overly strong southern ITCZ rain band, resulting in double-ITCZ bias in annual mean precipitation. In this study, we investigate the impact of convection parameterization scheme on the double-ITCZ bias in the NCAR Community Earth System Model, version 2.2 (CESM2.2). The standard CESM2.2 simulates a remarkable double-ITCZ bias in the central and eastern Pacific. Modifications to the closure in convection parameterization scheme greatly reduce the double-ITCZ bias, demonstrating that the convection parameterization can substantially influence the double-ITCZ bias in CESM2.2. Further analyses suggest that the convection parameterization can modulate the tropical atmosphere-ocean feedback processes, through which it influences the upper ocean temperature advections, sea surface temperature, and hence precipitation in the southern ITCZ region.

1. Introduction

Despite decades of climate model development, the large-scale distribution of precipitation simulated by coupled global climate models (GCMs) still displays significant biases over tropical oceans. Observations show a single zonal intertropical convergence zone (ITCZ) precipitation band north of the equator all year-round in the central and eastern tropical Pacific, with a much weaker zonal rain band south of the equator (southern ITCZ) observed only in boreal spring (Zhang, 2001). However, coupled GCMs tend to simulate overly strong southern ITCZ rain band for more than half of the year in the central and eastern tropical Pacific, resulting in the appearance of a double-ITCZ bias in annual mean precipitation (Mechoso et al., 1995; Lin, 2007; Zhang et al., 2015; Tian and Dong 2020). The double-ITCZ bias is especially remarkable in boreal winter and spring.

In the past decades, a number of hypotheses have been proposed for the possible root causes of the double-ITCZ bias. However, even today, there is still no consensus among scientists on the formation mechanism of the double-ITCZ bias. Early studies attributed the double-ITCZ bias to the local warm SST bias in the southeastern Pacific associated with the underestimated stratus cloud off the west coast of South America (Ma et al. 1996; Yu and Mechoso, 1999). Sensitivity experiments with modified cloud cover show the alleviation of double-ITCZ bias in the southern Pacific, however, the cold and dry tongue biases in SST and precipitation were exacerbated. It was later argued that the tropical double-ITCZ bias may be remotely caused by extratropical biases in cloud and radiation over the Southern Ocean through energetic constraint (Hwang and Frierson, 2013). However, a few follow-up studies disagree on this remote mechanism (e.g., Kay et al., 2016; Hawcroft et al., 2017). Recently, Kim et al. (2022) explored the teleconnection mechanism from the Southern Ocean to the Tropical Pacific first suggested by Mechoso et al. (2016). They argued that the strength of teleconnection is strongly modulated by the substropical stratocumulus cloud-SST feedback in the southeastern tropical Pacific. The overly weak subtropical low cloud feedback in GCMs results in a much weaker contribution from extratropical biases to tropical double-ITCZ bias. Kawai et al. (2021) investigated the relationship between radiation bias over the Southern Ocean and the tropical double-ITCZ bias in Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2.0). They found that the modifications in stratocumulus scheme, shallow convection scheme, and cloud microphysics parameterization can reduce the radiation bias over the Southern Ocean. Correspondingly, the tropical double-ITCZ bias was also reduced to some extent. However, they also found that the double-ITCZ bias was still present even when the radiation bias was eliminated over the Southern Ocean, indicating that other processes may be responsible for the double-ITCZ bias. They hypothesized that deep convection and shallow convection schemes may play important roles. Bypassing the cloud-SST feedback issues by prescribing SST with observations in the southeastern subtropical Pacific in a coupled GCM CESM1, Song and Zhang (2016) found reduced double-ITCZ biases in the annual mean. However, the seasonal evolution still showed large precipitation biases in boreal spring. Lee et al. (2022) investigated the causes of double-ITCZ bias in GFDL CM2.1. Their analyses suggest the zonal-mean diagnostics poorly represent the spatial pattern of precipitation bias in the tropical pacific (e.g., double-ITCZ). They demonstrated that tropical precipitation bias is mostly locally driven from the tropical SST bias. By analyzing the severity of the double-ITCZ bias in CMIP5 models, Xiang et al. (2017) also revealed statistical evidence that the largest source of the double-ITCZ bias is from the tropics. Zhou and Xie (2017) analyzed the severity of the double-ITCZ bias in CMIP5 models and found that this bias is closely correlated with the land surface temperature bias.

As ITCZ precipitation is largely produced by deep convective clouds, deep convection parameterization schemes have also been considered as a major cause for double-ITCZ bias. Zhang and Wang (2006) examined the impact of a revised closure (Zhang, 2002) of the Zhang-McFarlane convection scheme (Zhang & McFarlane, 1995) in the NCAR Community Climate System Model, version 3 (CCSM3). They found that the spurious southern ITCZ precipitation band in the central equatorial Pacific is generally eliminated in boreal summer with the revised convective closure. As a result, the annual-mean double-ITCZ biases in precipitation, sea surface temperature (SST), wind stress, and upper ocean currents are all significantly reduced through a complex coupled feedback between convection, surface wind, upper-ocean currents, and SST (Song and Zhang, 2009; Zhang & Song, 2010). It should be noted that the double ITCZ biases in boreal winter and spring still exist in the CCSM3 with the revised convective closure. Alleviating the double-ITCZ bias in boreal winter and spring remains a challenging task. Zhang et al. (2019) provided a comprehensive review of the roles of the Southern Ocean radiation bias, southeastern Pacific cloud bias and convection parameterization in double ITCZ in GCMs.

Significant model developments greatly improved the capability and performance of the NCAR global climate model, with the Community Climate System Model (CCSM) upgraded to the Community Earth System Model (CESM). However, double-ITCZ biases still persist. To investigate the role of convection parameterization in the formation of double-ITCZ biases in the CESM, Song and Zhang (2018) further examined the impact of the revised convective closure (Zhang, 2002) on double-ITCZ biases in NCAR CESM1.2.1. They found that the double-ITCZ biases are generally eliminated in boreal summer and autumn but persist in boreal winter and spring when the revised convective closure is used, similar to the impact documented in Song and Zhang (2009). Song and Zhang (2018) then further implemented improvements in the trigger function and cloud model of the ZM convection scheme into CESM1.2.1 and found that the double-ITCZ biases are largely eliminated in all seasons with the improved convection scheme, although there is still a dry tongue bias over the equator. Their analyses show that other possible contributors, such as cloud biases off the western coast of South America and over the Southern Ocean, are barely changed in their simulations, leading to the conclusion that the convection scheme is the primary contributor to the formation of double-ITCZ biases in the CESM1.2.1.

Woelfle et al. (2019) investigated the evolution of double-ITCZ biases in 10 intermediate model versions through the development from CESM1 to CESM2. They found that the double-ITCZ biases in the southeast Pacific in CESM2 are greatly reduced as compared to its previous version (CESM1), although the global mean ITCZ position and cold tongue bias do not exhibit significant improvement. The evolution of the double-ITCZ biases across development simulations suggests that the improved ITCZ in the southeast Pacific can be associated with the reduction of warm bias in the underlying SST, which can be attributed to increases in low cloud cover and associated cloud radiative forcing. The improved cloud simulation in the southeast Pacific is further attributed to changes in the cloud microphysics scheme, which decrease drizzle rates and increase cloud fraction and lifetime. The analysis of drizzling bias (i.e., too frequent drizzling) and double-ITCZ bias in CMIP5 and CMIP6 models (Zhou et al. 2022) also supports this mechanism. The authors argued that the excessive drizzling rain in the stratocumulus region can lead to fewer low-level clouds, which increase the incoming solar radiation and thus the warm SST bias in the southeastern Pacific.

Ma et al. (2023) assessed the double-ITCZ bias in the models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) and found that the models with relatively low double-ITCZ bias tend to restrain the frequency of deep convection effectively, highlighting that the convective process is crucial for mitigating the double ITCZ bias in coupled GCMs.

In this study, we examine the impact of convective closure on double-ITCZ bias in the newest version of NCAR CESM, CESM2.2 (Herrington et al. 2022). It is shown that the revised convective closure (Zhang 2002) eliminates the double-ITCZ biases not only in boreal winter and spring but also in summer and autumn in CESM2.2, which is different from its performance in CESM1.2.1, where it can only eliminate the double-ITCZ biases in boreal summer and autumn, indicating that changes in other model parameterizations can modulate the impact of the convection scheme and hence influence the formation of double–ITCZ biases. Since the revised convective closure can eliminate double-ITCZ bias in all seasons, it provides us a good opportunity to understand how convection parameterization influences the double-ITCZ biases in CESM. Detailed feedback analyses are performed to enhance our understanding on this issue.

The rest of paper is organized as follows: Section 2 briefly describes the model, convective closure, simulations, and observational data. Section 3 presents the impacts of the convective closure on the double-ITCZ bias in the CESM2.2. Section 4 analyzes coupled feedback mechanism through which the convective parameterization influences the double-ITCZ biases. Section 5 summarizes the results and conclusions.

2. Model, experiments, and data

a. Model and the revised convective closure

The NCAR Community Earth System Model, version 2.2 (CESM2.2), is used in this study. The CESM2.2 is a fully coupled, state-of-the-art, global climate model. The component models include the Community Atmosphere Model version 6 (CAM6, Danabasoglu et al., 2020), the

Community Land Model version 5 (CLM5), the Los Alamos sea ice model version 5 (CICE5), the Parallel Ocean Program version 2 (POP2), Community Ice Sheet Model (CISM) version 2.1, the Model for Scale Adaptive River Transport (MOSART), and NOAA WaveWatch-III ocean surface wave prediction model. In the CAM6, the moist boundary layer, shallow convection, and cloud macrophysics are parameterized with the Cloud Layers Unified by Binormals (CLUBB) scheme, and the large-scale cloud and precipitation processes are parameterized with an improved two-moment prognostic bulk cloud microphysics scheme (MG2, Gettelman and Morrison 2015). The Zhang and McFarlane convection scheme with a dilution approximation for the calculation of convective available potential energy (CAPE, Neale et al. 2008) is used for deep convection.

The default ZM convection scheme in CESM2.2 employs a CAPE-based closure, which assumes that convection acts to consume CAPE in a specified relaxation time period. Therefore, the convection intensity is proportional to the amount of CAPE. Zhang (2002) proposed a revised closure which assumes that the CAPE generation rate by large-scale forcing in the free troposphere can be approximately balanced by the CAPE consumption rate due to convection. That means the convection intensity is proportional to the CAPE generation rate instead of the amount of CAPE. Song and Zhang (2009, 2018) demonstrated that this closure can reduce the double-ITCZ bias in boreal summer in CCSM3 and CESM1.2.1, respectively. In this study, we employ this revised closure in the ZM convection scheme in CESM2.2 to investigate its impact on the double-ITCZ bias. In the experiment, although we do not modify the original CAPE-based trigger in the ZM convection scheme, when the dCAPE closure is applied in the convection scheme, it in effect also serves as a trigger. This is because when dCAPE$\leqslant$0 the cloud base mass flux is zero, meaning that convection is not triggered. A dCAPE-based trigger was used in E3SM by Xie et al. (2019).

b. Simulations

Two 11-year fully coupled simulations of CESM2.2 are conducted: one using the default version of the ZM convection scheme (referred to as the CTL run), and another using the ZM scheme with the revised closure (referred to as the RZM run). Both simulations employed B1850 component setting and f09_g17 grid configuration, which means that a 0.9°x1.25° resolution (latitude x longitude) is used in both atmospheric and land models. Version 7 of 1° Greenland Pole ocean/ice grid is used for ocean and sea ice models. The 5-year averages for years 7–11 are used to analyze the double-ITCZ bias in this study.

To identify the contribution of air-sea feedback in the formation of double-ITCZ bias and understand the impact of the revised convective closure on the atmospheric response to fixed SST, a set of 7-year Atmospheric Model Intercomparison Project (AMIP) type simulations are conducted using the CESM2.2. The AMIP simulation with the standard ZM scheme is referred to as CTL_amip, whereas the simulation using the revised closure in ZM convection scheme is referred to as RZM_amip. Both simulations employed F1850 component setting and f09_f09 grid configuration, which means the atmosphere model is driven by forcing (e.g., SST) in 1850 with a 0.9°x1.25° resolution (latitude x longitude). The 5-year averages for years 3–7 are used in the analyses.

c. Observational data

The Global Precipitation Climatology Project (GPCP) Version 3.2 precipitation analysis from 1983 to 2021 (Huffman et al. 2023), SST from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset between 1870 and 1900 (Rayner et al. 2003), the monthly mean meridional/zonal wind speed and pressure vertical velocity from ECMWF Reanalysis v5 (ERA5) (Hersbach et al. 2020) from 1979 to 2019, GCM-Oriented CALIPSO Cloud Product (CALIPSO-

GOCCP, Chepfer et al. 2010) from 2007 to 2010, and Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) from 2001-2018 (Kato et al. 2018) are used in the simulation evaluation.

3. Impacts of the convective closure on the double ITCZ bias

Figure 1 shows precipitation from the GPCP observation, the CTL and RZM simulations, along with their differences, averaged in boreal winter (December, January, February, DJF) and spring (March, April, May, MAM), respectively, when the double-ITCZ biases are most prominent. In winter, the GPCP observations show a southeastward SPCZ rain band south of the equator and only one zonal ITCZ rain band north of the equator, forming a strikingly asymmetric structure relative to the equator. Precipitation of >4 mm day^{-1} is confined to the west of 150°W between 2°S-10°S. CTL simulates two zonal rain bands straddling the equator across the Pacific, with precipitation of >4 mm day^{-1} extending to the west coast of south America between 2°S-10°S, demonstrating a typical double-ITCZ bias. Compared to its previous version (CESM1.2.1, Song and Zhang 2018, Fig.1c), CESM2.2 does not simulate a notable dry tongue bias over the equator. The overestimated precipitation in the southern ITCZ region between 120°W and 150°W is also reduced, indicating the double-ITCZ bias was mitigated due to model development from CESM1 to CESM2.2. With the revised closure, the spurious southern ITCZ rain band in the central and eastern Pacific is generally eliminated in the RZM simulation. Precipitation of >4 mm day^{-1} is confined to the west of 150°W between 2°S-10°S. Precipitation of < 4 mm day^{-1} is extended to 180° near the equator. Both of these changes lead RZM to good agreement with GPCP observations. The difference between CTL and GPCP clearly shows that CTL simulates a spurious southern ITCZ rain band in central and eastern Pacific with overestimated precipitation up to 5 mm day^{-1}. The RZM reduces the positive precipitation bias in the central and eastern Pacific between 2°S and 10°S by up to 4 mm day^{-1}, resulting in the double-ITCZ bias being largely eliminated.

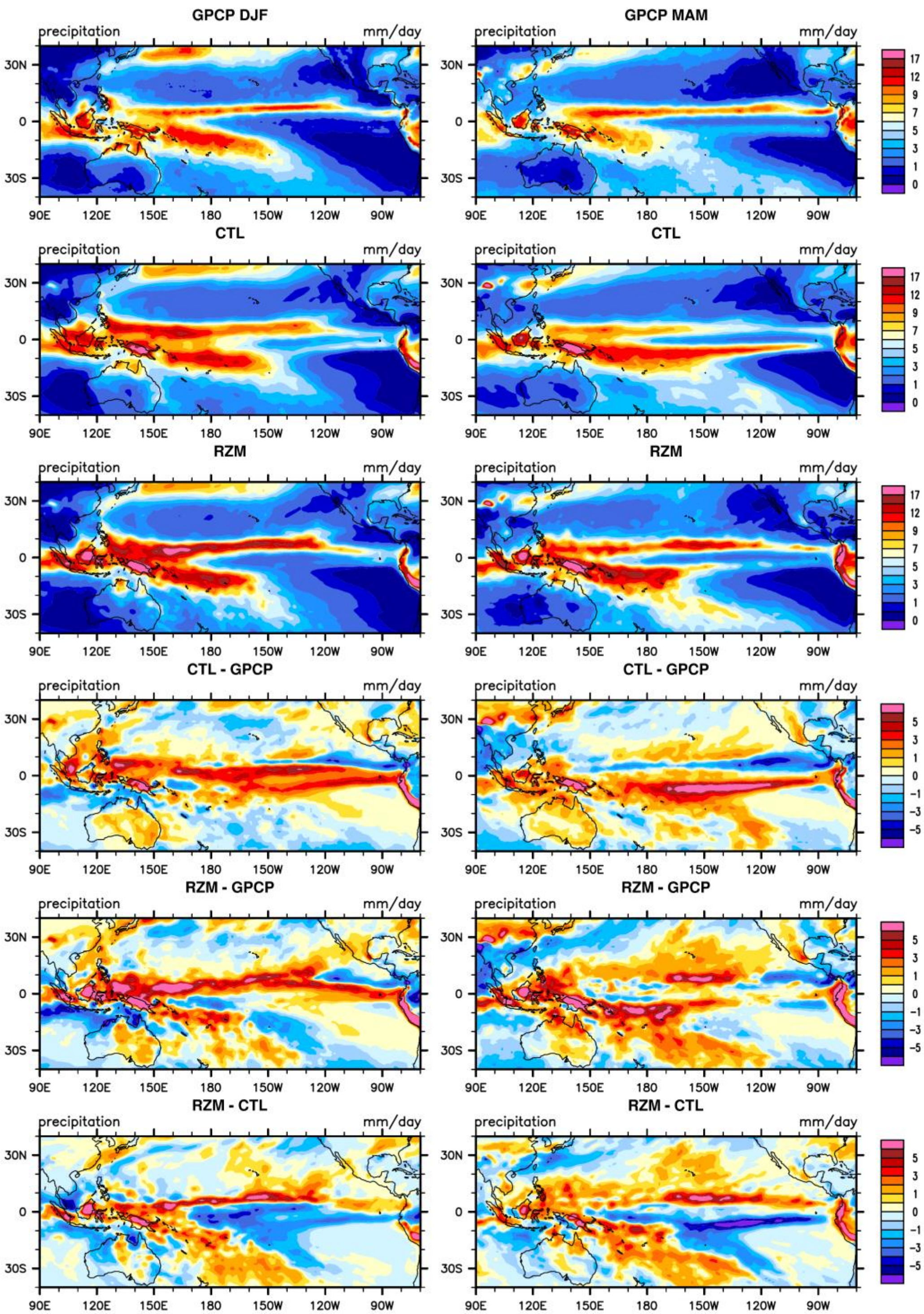

Figure 1 Precipitation (mm day^{-1}) from GPCP, CTL, RZM and their difference for DJF (left column) and MAM (right column).

In boreal spring, GPCP observation shows two parallel zonal rain bands in central and eastern Pacific, with the southern ITCZ being much weaker than the northern ITCZ. The precipitation in the southern ITCZ region is generally below 4 mm day^{-1}. CTL simulates an opposite precipitation distribution compared to observation, with a much stronger southern ITCZ rain band than the northern ITCZ. The simulated precipitation is up to 12 mm day^{-1} in the southern ITCZ region, which contributes significantly to the double-ITCZ bias in annual mean precipitation. The RZM generally reproduces the observed asymmetric distribution of precipitation in central and eastern Pacific. The simulated precipitation is about 4 mm day^{-1} in southern ITCZ the eastern Pacific, although it still slightly overestimates the southern ITCZ precipitation in central pacific. The difference between CTL and GPCP clearly shows that CTL overestimates precipitation by up to 7 mm day^{-1} in southern ITCZ and underestimates precipitation by up to 6 mm day^{-1} in northern ITCZ in central and eastern Pacific. The RZM reduces the positive precipitation bias between 2°S and 10°S by up to 7 mm day^{-1} and increases negative precipitation bias between 2°N-10°N by up to 7mm day^{-1} in central and eastern Pacific, indicating that the double-ITCZ bias in spring is largely eliminated as well.

In boreal summer (June, July, and August, JJA), the observed SPCZ precipitation (Fig.2a) retracts into the western Pacific with precipitation of >7 mm day^{-1} located west of 170°E between 2°S and 10°S. However, the CTL still tends to simulate too zonally elongated southern Pacific rain band with precipitation of > 7 mm day^{-1} extending eastward to 160°W between 2°S and 10°S, resulting in double-ITCZ bias in the western Pacific. Note that the double-ITCZ bias simulated by its previous version (CESM1.2.1,) in summer (Song and Zhang 2018, Fig.2f) is pronounced in both the western and central Pacific, demonstrating that model development from CESM1 to CESM2.2 substantially mitigated the double-ITCZ bias in the central Pacific in the

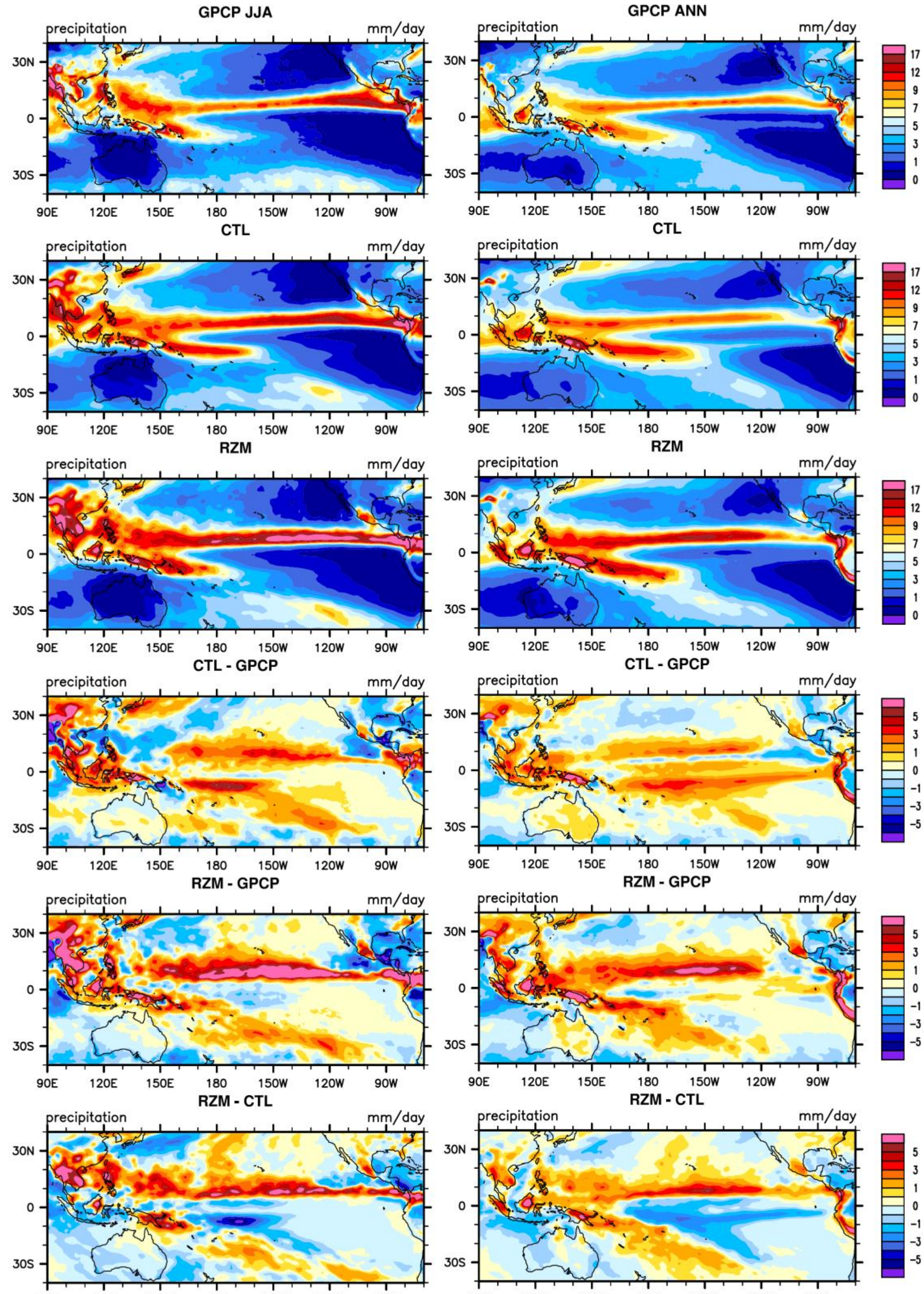

Figure 2 Same as Fig. 1 but for JJA (left column) and annual mean (ANN, right column).

summer season. The SPCZ precipitation simulated by RZM is in good agreement with GPCP observations with precipitation of > 7mm day^{-1} west of 180°, indicating that the revised convective closure can generally eliminate double-ITCZ bias in summer as well. The impact of revised convective closure on double-ITCZ bias in boreal autumn is similar to that in summer (not shown). As a result, the RZM completely eliminates the double-ITCZ bias in the central and eastern Pacific in annual mean precipitation. The annual-mean precipitation of > 3 mm day^{-1} simulated by RZM between 2°S and 10°S is located west of 145°W, which is in good agreement with the observations. In contrast, the annual-mean precipitation of > 3 mm day^{-1} simulated by CTL between 2°S and 10°S is extended all the way to 90°W, resulting in remarkable double-ITCZ biases in the central and eastern Pacific.

To quantitatively evaluate the changes in double-ITCZ bias, we calculate the Pacific ITCZ pattern index, which is defined as the difference between the northern ITCZ (2°N-10°N, area-averaged) precipitation and the southern ITCZ (2°S-10°S, area-averaged) precipitation normalized by the tropical mean precipitation (10°S-10°N) in the central and eastern Pacific over 85°W-160°W. This pattern index reflects the interhemispheric asymmetry in ITCZ precipitation in the central and eastern Pacific, where the double-ITCZ bias is most prominent. Similar global index has been widely used in past research (e.g., Hwang & Frierson, 2013; Tian and Dong, 2020). Table 1 shows the Pacific ITCZ pattern index from GPCP, RZM and CTL simulations. Positive values mean that the northern ITCZ precipitation is stronger than the southern ITCZ. The ITCZ pattern index from GPCP reveals that the northern ITCZ is stronger than the southern ITCZ all year-round in observations, with weaker interhemispheric asymmetry in boreal winter and spring. However, CTL simulates a negative ITCZ pattern index in spring, reflecting that the southern ITCZ precipitation is stronger than its northern counterpart. CTL also simulates a very weak ITCZ pattern index in winter. As a result, the annual mean ITCZ pattern index simulated by CTL is only about half of the observation, indicating a large double-ITCZ bias because the southern ITCZ precipitation simulated by CTL is more comparable to the northern ITCZ. RZM successfully reproduces the observed ITCZ pattern index, especially in annual mean precipitation, demonstrating that the double-ITCZ bias is generally eliminated with the revised convective closure. Although the widely used ITCZ pattern index can represent the interhemispheric asymmetry of ITCZ precipitation, it does not directly assess the southern ITCZ precipitation bias and double-ITCZ bias. We further define a double-ITCZ bias index as the ratio of southern ITCZ (2°S-10°S) precipitation relative to northern ITCZ (2°N-10°N) precipitation in the central and eastern Pacific over 85°W-160°W. When there is only a single ITCZ, the double–ITCZ bias index will be very close to zero, while when there is a double-ITCZ the double–ITCZ bias index will be close to or larger than one. Table 2 shows the double-ITCZ bias index from GPCP, RZM and CTL simulations. The double-ITCZ bias index from GPCP reveals that the southern ITCZ precipitation is only about 10% of northern ITCZ precipitation in summer and fall and increased to 44% in spring. In annual mean precipitation, the southern ITCZ is about 21% of northern ITCZ. The double-ITCZ bias index simulated by CTL is about three times as large as that in observations in winter and spring, indicating a remarkable double-ITCZ bias. Again, RZM successfully reproduces the observed double-ITCZ bias index, not only in annual mean but also for all seasons, demonstrating that the double-ITCZ bias is generally eliminated with the revised convective closure. However, although the revised closure significantly improves the simulation of the asymmetric distribution of ITCZ precipitation with respect to the equator, it generally tends to simulate stronger ITCZ precipitation than observed.

Table 1. Pacific ITCZ pattern index from GPCP, RZM and CTL simulations.

ITCZ pattern index	ANN	DJF	MAM	JJA	SON
GPCP	1.545	1.481	0.897	1.948	2.128
RZM	1.544	1.333	0.803	2.087	2.013
CTL	0.828	0.522	-0.377	1.767	1.914

Table 2. Double-ITCZ bias index from GPCP, RZM and CTL simulations.

Double-ITCZ bias index	ANN	DJF	MAM	JJA	SON
GPCP	0.21	0.22	0.44	0.11	0.07
RZM	0.20	0.23	0.47	0.07	0.09
CTL	0.46	0.59	1.41	0.15	0.11

Convection-circulation interaction is one of the most important processes through which convection parameterization schemes influence climate simulation. Fig.3 presents the annual mean vertical velocity (shaded) and zonal circulation (streamline) averaged over the southern ITCZ region (2°S-10°S) from ERA5, CTL and RZM simulations. ERA5 shows a typical Walker circulation with deep ascending motion west of 170°W, deep descending motion east of 160°W, and easterly wind in the lower troposphere. Corresponding to the zonally elongated southern ITCZ rain band, the deep ascending motion regime in CTL is extended eastward to 160°W, with the regime of shallow ascending motion extending to 100°W. RZM successfully reproduces the observed Walker Circulation, with deep ascending motion west of 170°W and deep descending motion east of 160°W. The difference between RZM and CTL clearly shows that the modified convective closure induces increased descending motion in the central and eastern Pacific, stronger ascending motion in the western Pacific, and enhanced easterly winds in the lower troposphere.

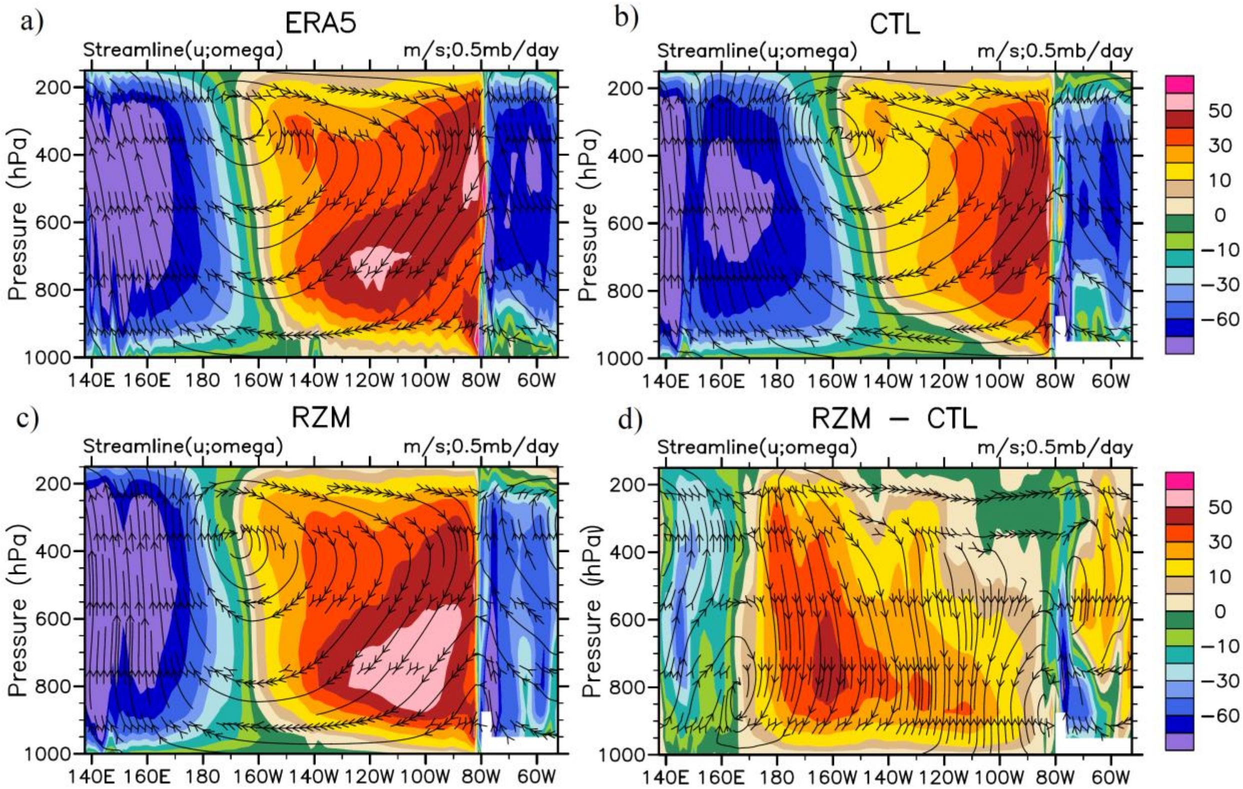

Figure 3 zonal-pressure cross section of annual mean pressure vertical velocity (0.5 mb day^{-1}) and streamline from ERA5, CTL, RZM, and the difference between RZM and CTL, averaged over the southern ITCZ region (2°S-10°S).

Previous studies attributed the double-ITCZ precipitation bias to the low-level cloud bias in the southeastern Pacific. Fig.4 evaluates the annual mean low-level cloud simulations from RZM and CTL. Compared to CALIPSO-GOCCP observations, the CTL underestimates the low-level cloud fraction by up to 40% in the southeastern Pacific. With the modified convective closure, the low-level cloud fraction is increased by up to 20% in the southeastern Pacific. Correspondingly, the shortwave cloud forcing (not shown) in the same region is increased by up to 20 Wm^{-2} in RZM, which would contribute to SST cooling there.

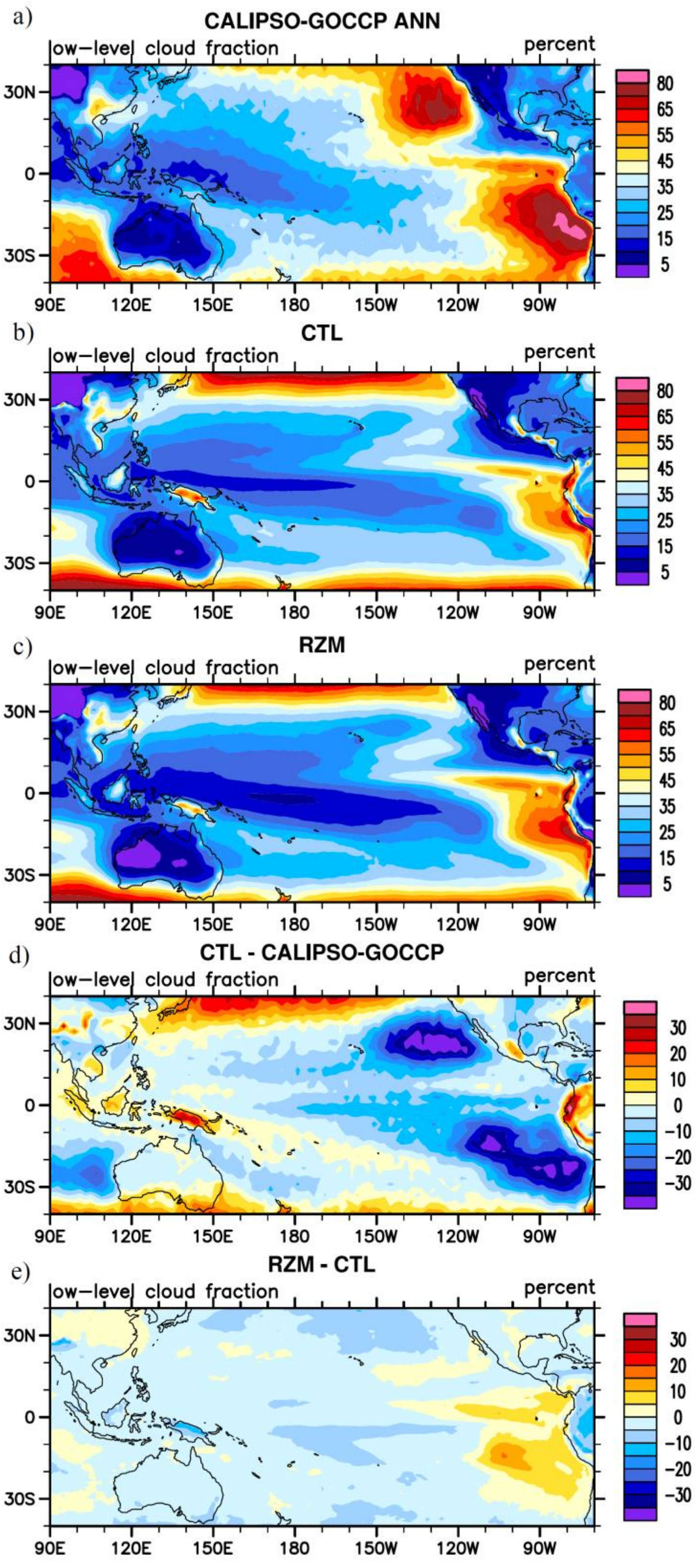

Figure 4 Annual mean low-level cloud fraction (%) from CALIPSO-GOCCP, CTL, RZM and their differences.

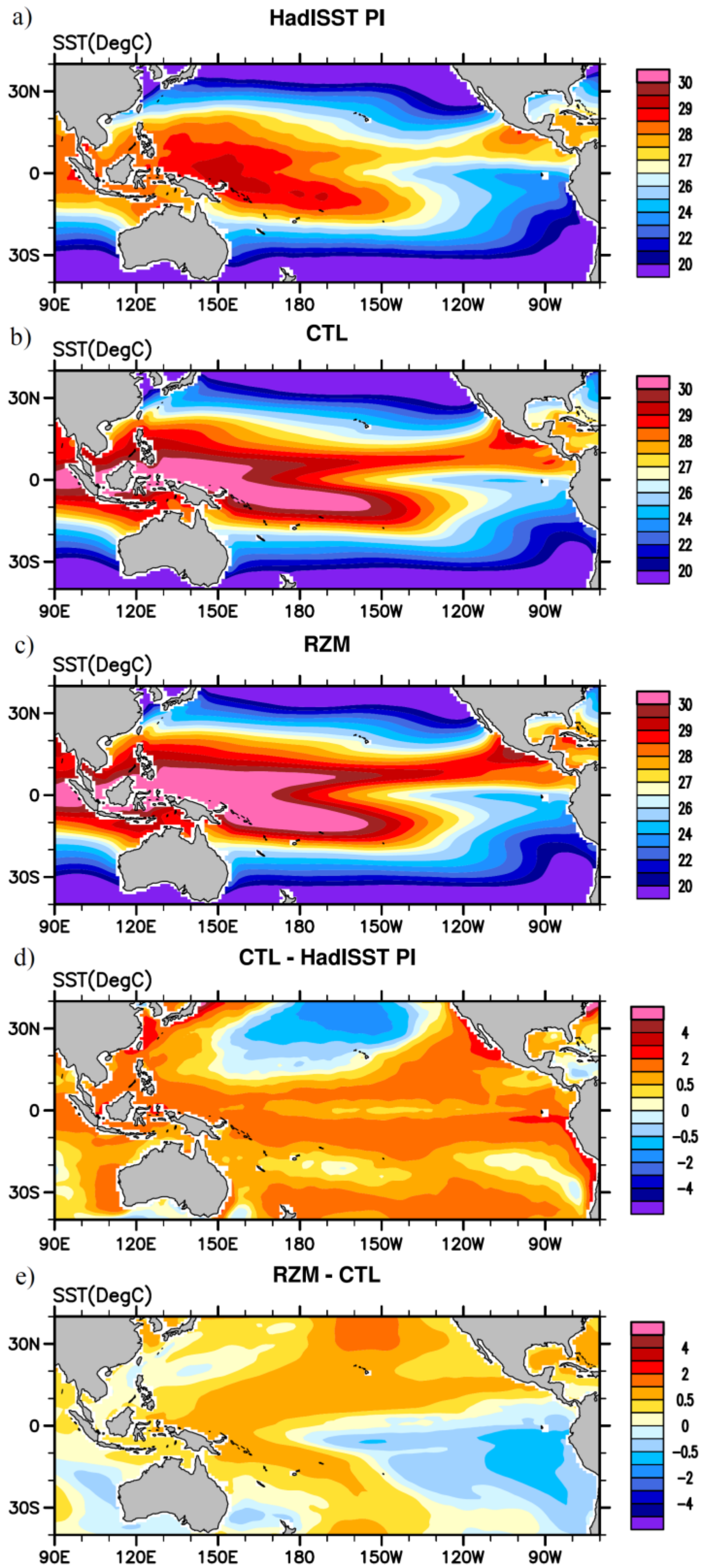

Figure 5 Annual mean sea surface temperature (SST) from HadISST, CTL, RZM, and their differences.

Figure 5 presents the annual mean SST from HadISST, the CTL and RZM simulations, along with their differences. The average SST from HadISST between 1870 and 1900 is used as observed PI climatology. It shows warm SST in the tropical western Pacific warm pool and cold SST in the tropical southeastern Pacific. The tropical western Pacific warm pool, an area where SST is higher than 28°C, coincides with the SPCZ precipitation region south of the equator, demonstrating that SST may substantially modulate deep convection. Corresponding to the overly strong southern ITCZ convection as manifested by the excessive precipitation, the CTL simulates a warm SST bias by up to 2°C between 2°S and 10°S in the Pacific Ocean. With the revised convective closure, the RZM simulates colder SST by up to 1°C than CTL between 2°S and 10°S in the Pacific Ocean, corresponding to the elimination of the precipitation bias in the southern ITCZ region.

The SST difference between RZM and CTL in the southern ITCZ region indicates that the revised convective closure triggers atmosphere-ocean feedback, which reduces the warm SST bias in the southern ITCZ region and hence eliminates the double-ITCZ bias in precipitation. To verify the important roles of SST change and associated coupled feedback, Fig.6 shows the annual mean precipitation bias simulated by the CTL_AMIP and RZM_AMIP. Compared to the CTL, the CTL_AMIP simulates very weak double-ITCZ biases in the central Pacific and does not simulate double ITCZ biases in the eastern Pacific, demonstrating that the atmosphere–ocean feedback and associated SST changes play critical roles in the formation of the double ITCZ bias. Compared to the CTL_AMIP, the RZM_AMIP simulates stronger convection in the western Pacific and weaker convection in the central Pacific between 2°S and 10°S. How do these changes induced by the revised closure influence the atmosphere–ocean feedback and SST changes in RZM, and hence influence the double-ITCZ bias? We conduct coupled feedback analyses in the next section to answer this question.

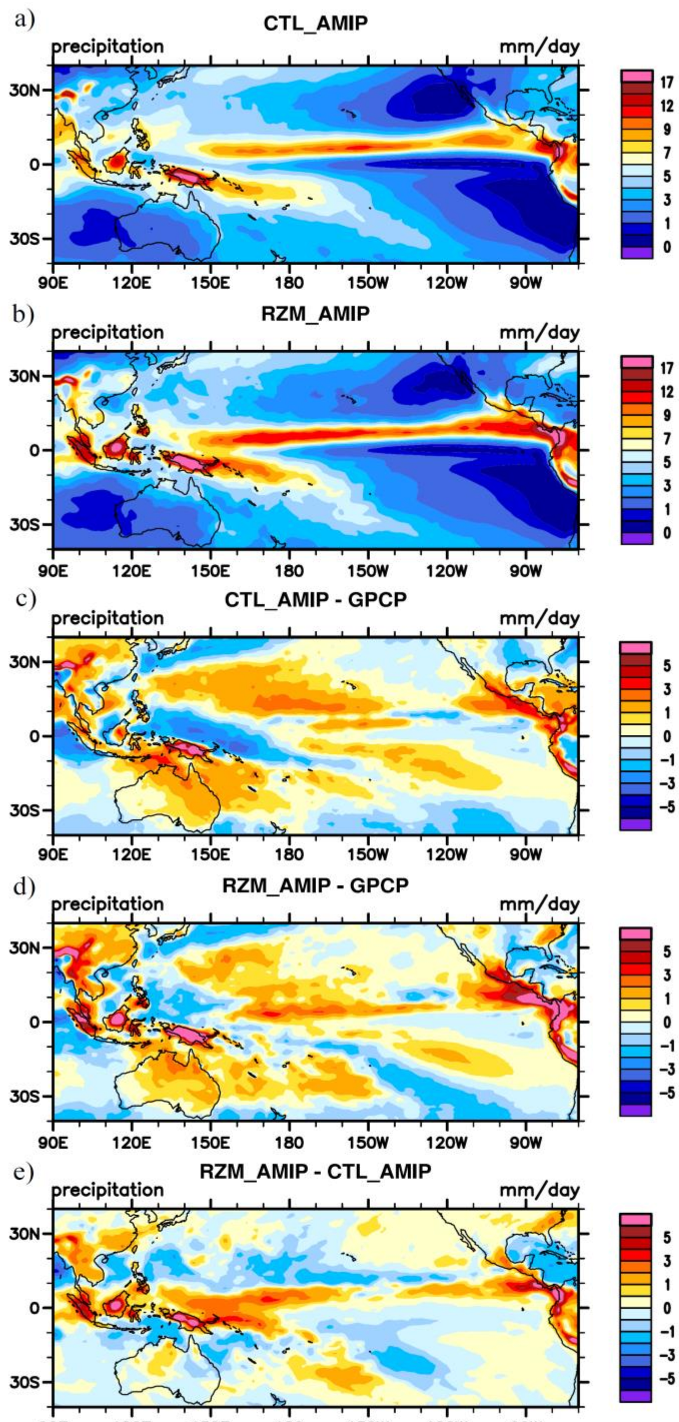

Figure 6 Annual mean precipitation (mm day^{-1}) from CTL_AMIP, RZM_AMIP, and their difference (RZM_AMIP-CTL_AMIP). Annual mean precipitation biases relative to GPCP from CTL_AMIP (CTL_AMIP-GPCP) and RZM_AMIP (RZM_AMIP-GPCP).

4. Coupled feedback analyses

To understand how the change in the convective scheme in atmosphere model leads to SST cooling in ocean model in the southern ITCZ region, we first perform a heat budget analysis of the ocean mixed layer in the southern ITCZ region. The temperature equation for the ocean mixed layer can be written as (Moisan and Niiler, 1998):

$$\frac{\partial T_a}{\partial t} = \frac{Q - Q_s(-h)}{\rho c_p h} - u_a \frac{\partial T_a}{\partial x} - v_a \frac{\partial T_a}{\partial y} - \frac{(T_a - T_{-h})}{h}(w_e + w_{-h}) + R \qquad (1)$$

where $T, u,$ and v represent temperature, zonal and meridional currents velocities in mixed layer, respectively. Subscript a represents the vertical average over the mixed layer depth h. Q is the net surface energy flux into the top of mixed layer, and $Q_s(-h)$ is the shortwave radiative flux penetrating through the base of the mixed layer. ρ [1026 kg m^{-3}] is the reference density of seawater, and c_p [3996 J kg^{-1} K^{-1}] is the specific heat of seawater at constant pressure. $T_{-h}$is the temperature just below the mixed layer. $w_e + w_{-h}$is the entrainment velocity, where $w_e = \frac{dh}{dt} = \frac{\partial h}{\partial t} + u_{-h}\frac{\partial h}{\partial x} + v_{-h}\frac{\partial h}{\partial y}$, u_{-h} and v_{-h} are the zonal and meridional current velocities at the mixed layer base, respectively. w_{-h} is the vertical current velocity at the mixed layer base. On the right-hand side of Eq. (1), the first four terms represent the temperature changes due to net energy flux into the mixed layer, zonal advection, meridional advection, and vertical entrainment, respectively. The fifth term, R, represents the residual term, which consists of the integral of the vertical temperature-velocity covariance and horizontal diffusion.

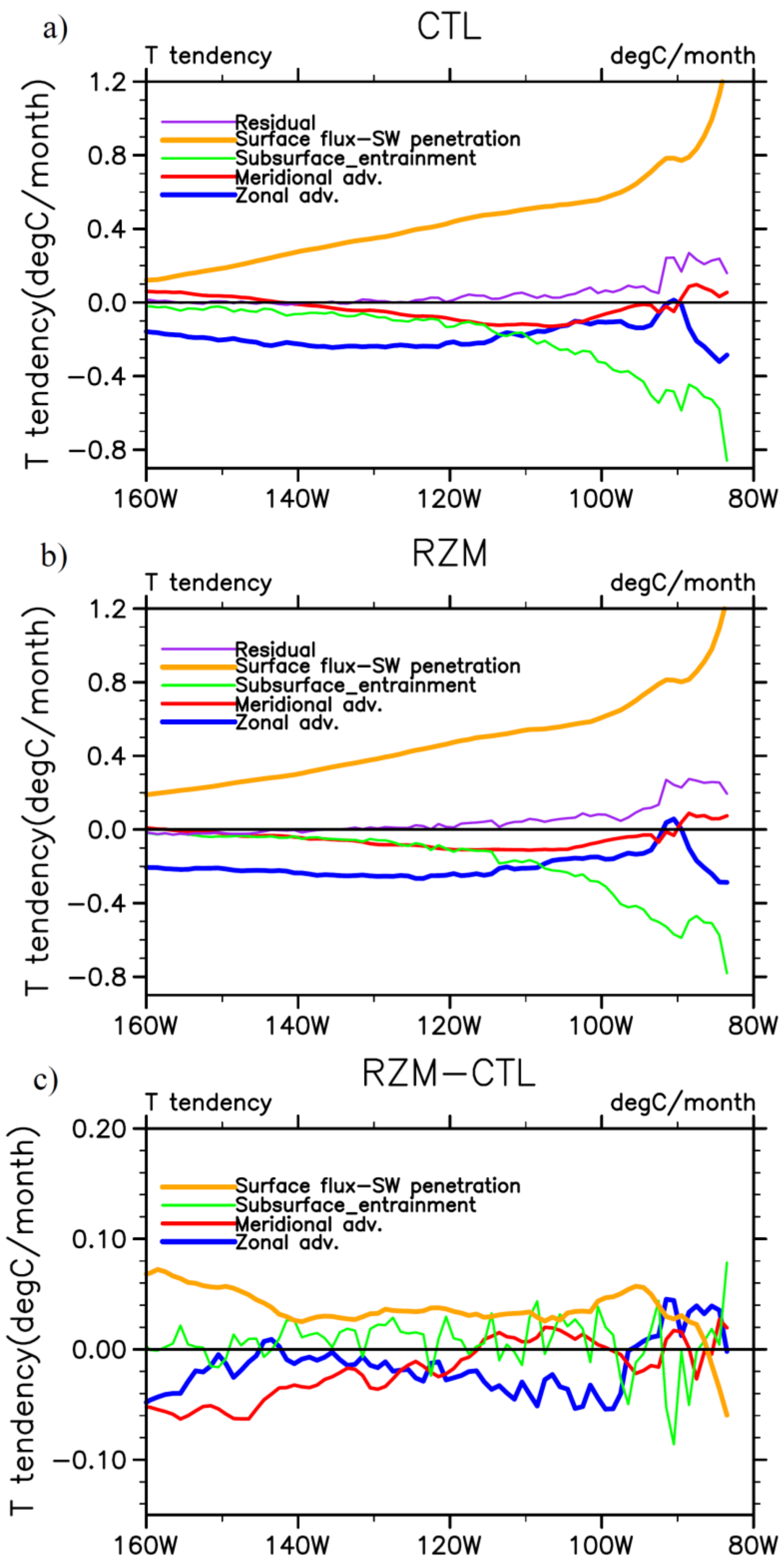

Figure 7 Annual mean temperature tendencies of the ocean mixed layer averaged over the southern ITCZ region (2°S-10°S) from each term on the right-hand side of Eq. (1) for a) CTL, b) RZM, and c) the difference between RZM and CTL.

The ocean mixed layer heat budget analysis is performed using monthly mean data from the model simulations following Liu et al. (2012). Figure 7 shows the annual mean of temperature tendencies contributed by each term to the mixed layer temperature in the southern ITCZ region (2°S-10°S). The residual terms in both CTL and RZM are very close to zero in the central and eastern Pacific from 160°W to 90°W. Near the coast, the residual terms are increased slightly but are still much smaller than the major warming/cooling terms. These demonstrate that the heat budget analysis is reasonably accurate. In both CTL and RZM, the major heating term for the ocean mixed layer is the surface heat flux, primarily balanced by cooling due to zonal advection, which transports cold water from east to west between 110°W to 160°W. East of 110°W, the cooling due to vertical entrainment of cold water at the base of the mixed layer (i.e., upwelling of cold water) plays more important role. The difference between RZM and CTL suggests that the SST cooling in RZM is caused by different terms in different regions. In the central Pacific between 120°W and 160°W, the major cooling term is meridional advection, with some contribution from zonal advection between 150°W and 160°W. Zonal advection is the dominant cooling term between 100°W and 120°W. Vertical entrainment contributes to the SST cooling near 90°W, while the surface heat flux only produces cooling east of 87°W.

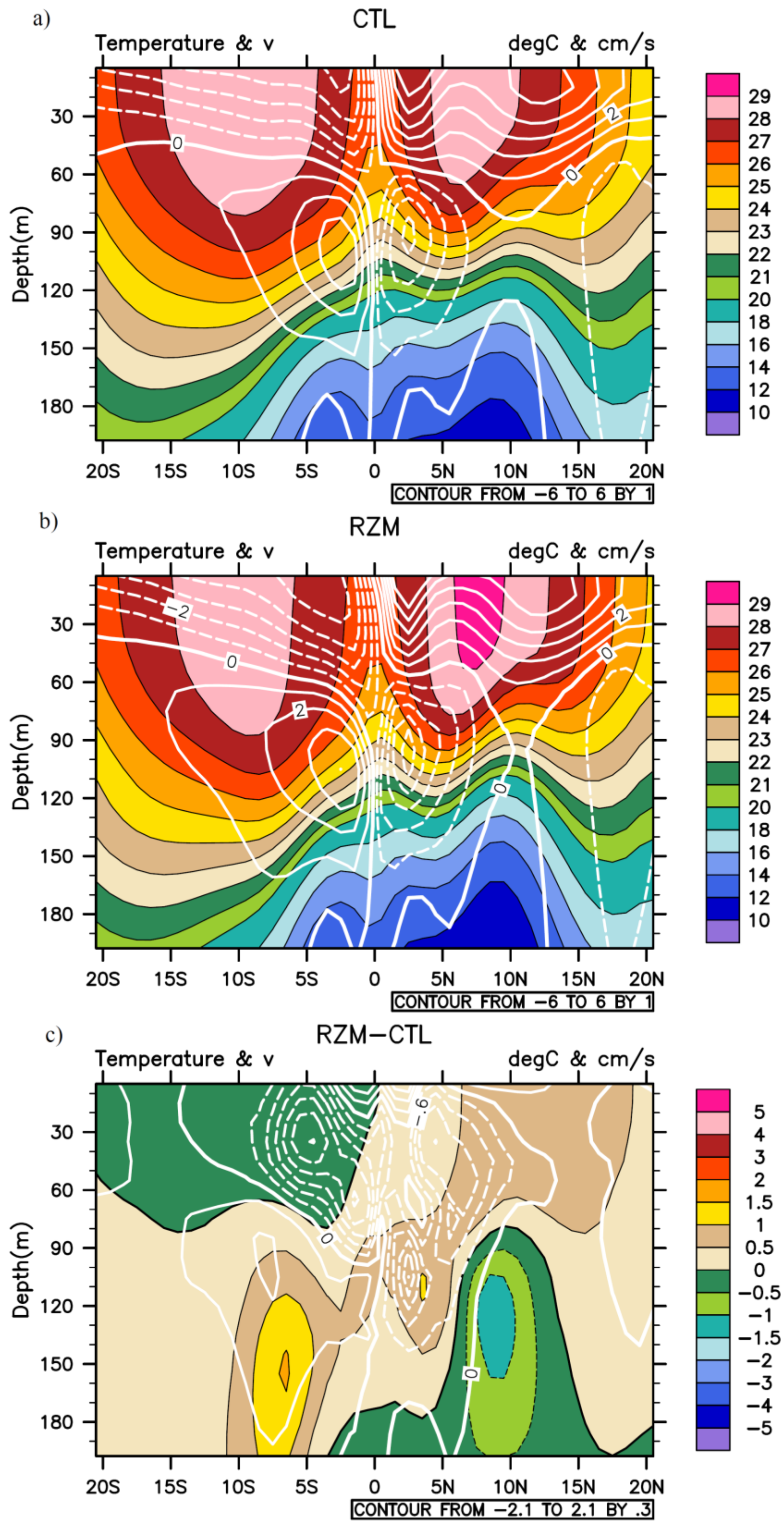

Figure 8 Annual mean upper ocean temperature (°C) and meridional current averaged over 120°W-160°W from a) CTL, b) RZM, and c) the difference between RZM and CTL.

To understand the mechanism through which meridional advection cools the SST in RZM in the central Pacific, Fig.8 presents the latitude-depth diagram of ocean temperature and meridional currents from RZM and CTL averaged over 120°W-160°W. Corresponding to the equatorial upwelling, equatorward currents below 50m generates mass convergence near the equator, while the poleward currents in the upper 50m produce mass divergence from the equator and cold meridional temperature advection to the southern ITCZ region. The difference between RZM and CTL clearly shows that mass divergence is enhanced in the upper 20m near 2°S, indicating the upwelling is enhanced in the RZM in the central Pacific. Since the equatorial upwelling is driven by surface wind, we further examine changes in zonal wind (shaded) and wind vectors from CTL to RZM in the atmospheric model averaged between 5°S and the equator in the longitude-height plane.

Fig.9a shows that the subsidence and low-level easterlies are enhanced in RZM in the equatorial central Pacific between 120°W and 160°W. The zonal wind speed and wind vector (u, v) differences between RZM and CTL at 925 hPa (Fig. 9b) further illustrate that the low-level easterlies are increased in the central Pacific over the southern ITCZ region. This is consistent with Fig.3, indicating that the Walker circulation is enhanced in RZM. This circulation change in RZM coincides with the precipitation (convection) change as shown in Fig.2, where convection is suppressed over equatorial central and eastern Pacific and enhanced over equatorial western Pacific in RZM.

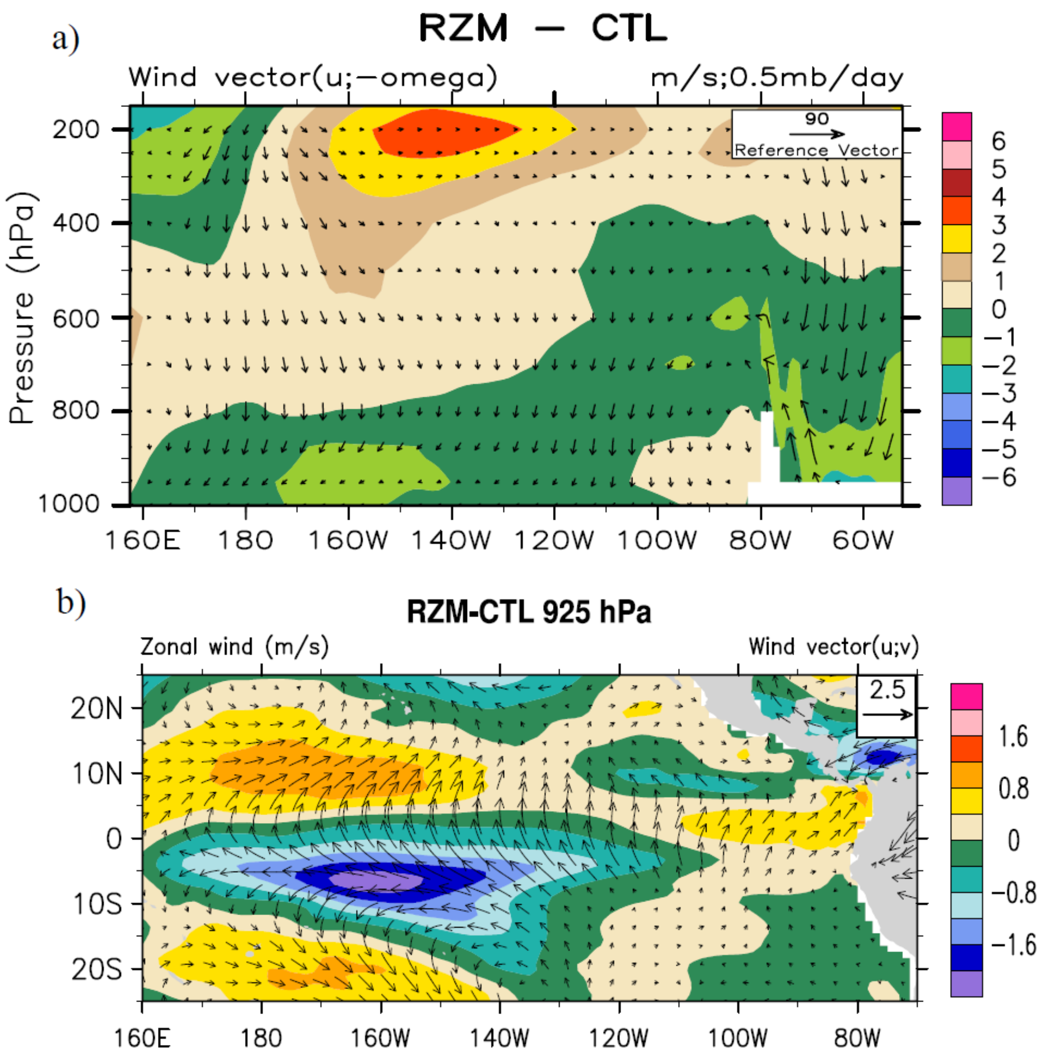

Figure 9 a) Zonal-pressure cross section of differences in annual mean zonal wind (m s^{-1}, shaded) and wind vectors (u: m s^{-1}; omega: 0.5 mb day^{-1}) between RZM and CTL, averaged over (0°-5°S). b) corresponding zonal wind speed and wind vector (u; v) differences between RZM and CTL at 925 hPa.

The convection changes in the coupled simulation introduced by the modified convective closure can be traced back to the AMIP simulation (Fig.6), which shows the modified convective closure tends to suppress convection in the central and eastern Pacific and enhance convection in the western Pacific. Therefore, the coupled feedback mechanism through which the modified convective closure mitigates the double-ITCZ bias in the central Pacific can be summarized as follows: The modified convective closure tends to suppress convection in the central Pacific. The low-level easterly then transports more water vapor to the western Pacific and enhances convection there. The convection changes strengthen Walker circulation and increase descending motion and low-level easterly in the central Pacific, which in turn suppress convection in the central Pacific and enhance convection in the western Pacific. In addition, the resultant increase in the surface easterly in the equatorial central Pacific may enhance equatorial upwelling in the ocean and produce stronger meridional divergence in the upper ocean. The enhanced poleward currents transport cold water to the southern ITCZ region and reduce SST there. The colder SST in the southern ITCZ region in the central Pacific may further suppress convection there and resultant feedback leads to the mitigation of double-ITCZ bias in the central Pacific.

To understand the role of changes in zonal temperature advection in the upper ocean in mitigating the double-ITCZ bias in the southern ITCZ region, Fig.10 presents the longitude-depth diagram of ocean temperature (shaded) and zonal currents averaged over 2°S-10°S from CTL and RZM, along with their differences. The ocean temperature gradually increases from the eastern to western Pacific. Corresponding to the surface easterly wind, the westward surface currents transport cold water from the eastern Pacific to the western Pacific, leading to cold temperature advection. The difference between RZM and CTL shows that both enhanced zonal currents and temperature gradient in RZM contribute to the increased cooling due to zonal temperature advection. The strengthening of zonal current can be attributed to the enhanced surface easterlies, as shown in Fig.3. As demonstrated in the ocean mixed layer heat budget analysis, the enhanced zonal temperature advection is the major contributor to the SST cooling in RZM between 100°W and 120°W, where the zonal gradient of ocean temperature is notably increased. The deep cooling of temperature from 140 m to the ocean surface east of 100°W indicates that the enhanced upwelling east of 100°W may contribute to the increased temperature gradient between 100°W and 120°W.

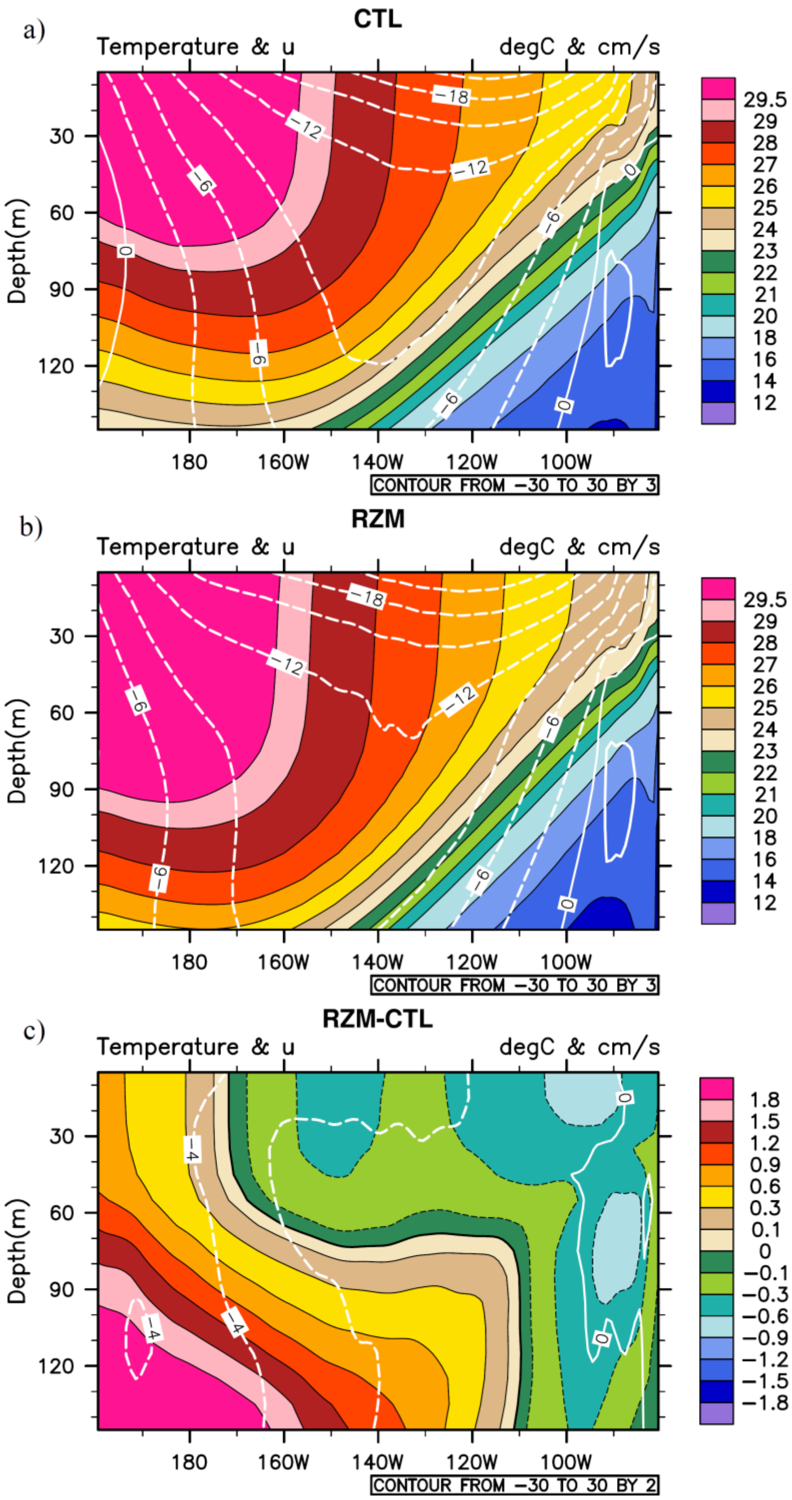

Figure10 Annual mean upper ocean temperature (°C) and zonal current (cm s^{-1}) averaged over 2°S-10°S from a) CTL, b) RZM, and c) the difference between RZM and CTL.

As discussed in Section 3, the modified convective closure improves the low-level cloud and shortwave cloud radiative forcing in the southeastern Pacific, which could result in SST cooling in RZM. However, the heat budget analysis of the ocean mixed layer shows that the change of net heat flux into the ocean mixed layer (the first term on the right-hand side of Eq. 1) in RZM only contributes to SST cooling in a very limited region (82°W-87°W) in the equatorial southeastern Pacific. Since the net surface heat flux into the mixed layer at the sea surface represents the net effect of its four components: shortwave radiative flux, longwave radiative flux, sensible heat and latent heat flux, we further analyze the contribution of these four components to the net surface heat flux change in RZM. Figure 11 shows the annual mean difference in the surface heat flux (into the ocean) components between RZM and CTL, averaged over 2°S-10°S. Comparing to CTL, the net surface heat flux into the ocean in RZM is increased slightly across the central and eastern Pacific from 160°W to 87°W and decreased over 87°W -82°W, indicating that the net surface heat flux changes in RZM may induce SST warming in most of the southern ITCZ region and only contribute to SST cooling in the region over 87°W-82°W. This also suggests that the changes in the other two factors in the net heat flux term of Eq. (1): mixed layer depth and shortwave radiative flux penetrating through the base of the mixed layer, have little impact on the SST change in RZM. The shortwave radiative flux into the ocean is increased in the region 110°W-160°W in RZM due to reduced convection and cloud, while it is decreased in the region 110°W-82°W because of the increase of low-level cloud. However, the net longwave radiative flux out of the ocean is also decreased (decrease in upward heat flux is equivalent to an increase in downward heat flux or relative heating) over 110°W-82°W due to the increase in low-level cloud. Additionally, the latent heat flux out of the ocean is decreased (thus less cooling or relatively more heating) due to weaker wind speeds. As a result, the net surface heat flux change in RZM only contributes to SST cooling in a very limited region (82°W-87°W) in the equatorial southeastern Pacific.

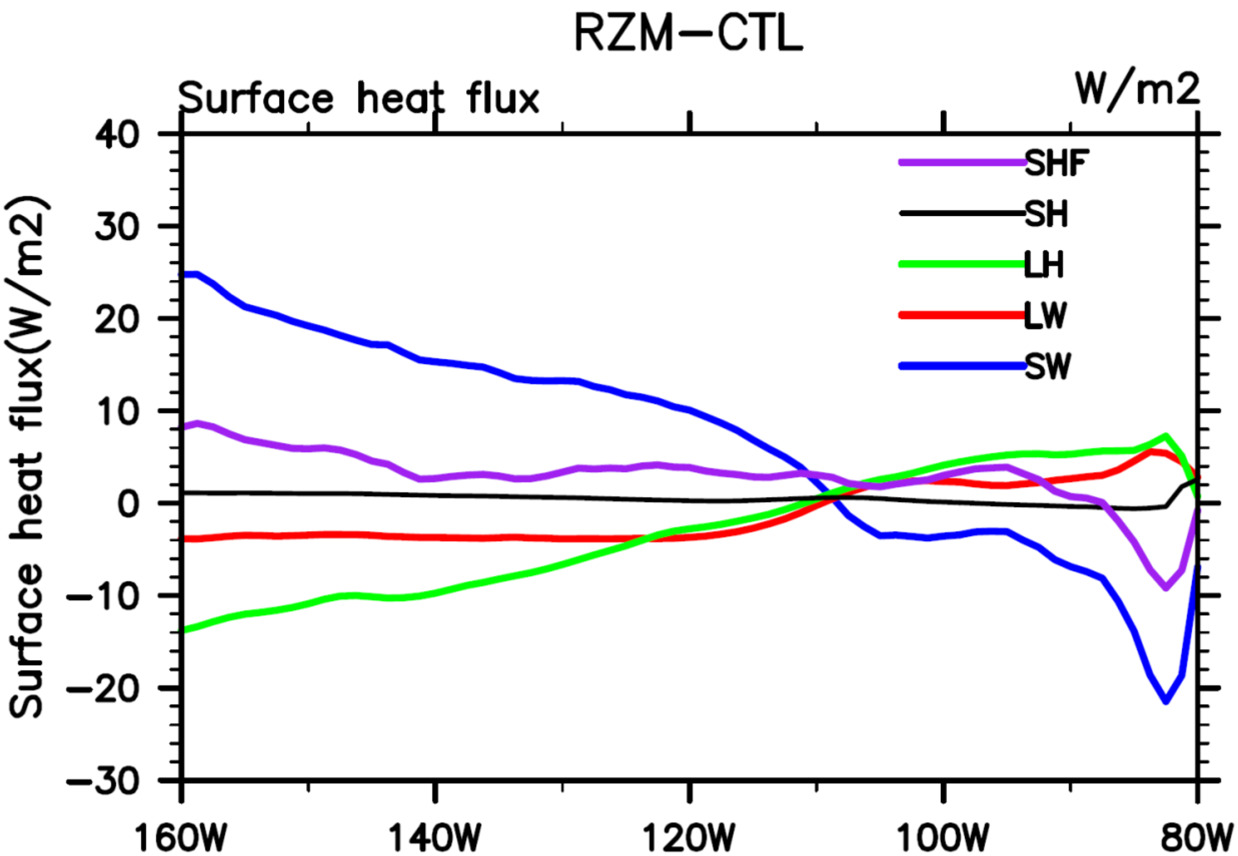

Figure 11 Differences in components of annual mean surface heat flux into the ocean: net surface heat flux (SHF), sensible heat flux (SH), latent heat flux (LH), longwave radiative heat flux (LW), and shortwave radiative flux (SW) between RZM and CTL, averaged over 2°S-10°S. All fluxes are defined as positive downward (into the ocean).

5. Summary and conclusions.

In this study, we examined the impact of convective closure on the double-ITCZ bias in the NCAR CESM2.2. Although the model development from CESM1.2 to CESM2.2 has significantly reduced the dry tongue bias over the equator and the excessive precipitation bias in the southern ITCZ region between 120°W and 150°W, the standard CESM2.2 still simulates a remarkable double-ITCZ bias in the central and eastern Pacific. In the spring, the simulated southern ITCZ is even stronger than the northern ITCZ, forming a reversed interhemispheric asymmetry. The revised convective closure greatly reduces the double-ITCZ bias in all seasons, demonstrating that convection parameterization can substantially influence the double-ITCZ bias in CESM2.2. It should be noted that the same closure change in CESM1.2.1 can only eliminate the double-ITCZ bias in summer and autumn, suggesting that other model process parameterizations, such as the cloud microphysics scheme and PBL scheme, may also contribute to the coupled feedback that influences the double-ITCZ bias. However, this study demonstrates that convection parameterization is one of the most important processes that can substantially influence the double-ITCZ bias.

The atmospheric model simulation of CESM2.2 forced by observed SST simulates a very weak double ITCZ bias in the central Pacific and does not simulate a double ITCZ bias in the eastern Pacific, demonstrating that the atmosphere–ocean feedback and associated SST changes play critical roles in the formation of the double-ITCZ bias. The fully coupled simulation of CESM2.2 produced warm SST biases in the southern ITCZ region, while the coupled simulation with modified convective closure significantly reduced the warm SST biases, indicating that convection parameterization in the atmosphere model can influence the ocean SST and double-ITCZ bias in precipitation through coupled feedback processes.

To understand how the convection parameterization scheme change in the atmosphere model leads to SST cooling in the ocean model in the southern ITCZ region, we perform the heat budget analysis of the ocean mixed layer in the southern ITCZ region. It shows that the modified convective closure introduces SST cooling through several mechanisms, each of which is dominant in different regions. In the central Pacific between 120°W-160°W, the major cooling is caused by meridional advection changes, with some contribution from zonal advection between

150°W and160°W. Further analysis suggests that the convective closure may influence the double-ITCZ bias through the following mechanism: The modified convective closure tends to suppress convection in the central Pacific. The low-level easterly then transports more water vapor to the western Pacific and enhances convection there. The changes in convection strengthen the Walker circulation and increase descending motion and low-level easterly winds in the central Pacific, which, in turn, suppress convection in the central Pacific and enhance convection in the western Pacific. Additionally, the resultant increase in surface easterly winds in the equatorial central Pacific may enhance upwelling in the ocean and produce stronger meridional divergence in the upper ocean. The enhanced poleward currents transport cold water to the southern ITCZ region and reduce SST there. The colder SST in the southern ITCZ region in the central Pacific may further suppress convection there, and the resultant feedback leads to the mitigation of the double-ITCZ bias in the central Pacific.

Between 100°W and 120°W, when the modified convective closure is used, the enhanced surface easterly wind drives stronger westward surface currents, which transport more cold water from the eastern Pacific to the central Pacific, resulting in the SST cooling in the southern ITCZ region. In this region, the zonal gradient of ocean temperature is also notably increased, which can be attributed to the enhanced upwelling east of 100°W.

Although the modified convective closure improves the low-level cloud and shortwave cloud radiative forcing in the southeastern Pacific, the surface heat flux only contributes to SST cooling in a very limited region (82°W-87°W) in the equatorial southeastern Pacific because the impacts shortwave radiation changes are largely canceled by changes in longwave radiation and latent heat flux.

In summary, this study demonstrates that convection parameterization substantially influences the double-ITCZ bias in CESM2.2 by modulating the coupled feedback, in which the equatorial upper ocean processes play important roles, while the could-radiation processes in equatorial southeastern Pacific play a limited role.

Acknowledgments

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Data Availability Statement

The observational datasets used in this study are available at: https://web.lcrc.anl.gov/public/e3sm/diagnostics/observations/Atm/climatology/. The simulation data used in this study can be found on Zenodo at https://zenodo.org/records/10702744.

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