Relationship between shortwave radiation bias over the Southern Ocean and the double-intertropical convergence zone problem in MRI-ESM2

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Abstract
The relationship between improvements in the radiation bias over the Southern Ocean and the alleviation of the double-intertropical convergence zone (ITCZ) problem in the actual updates of our climate models is investigated. The radiation bias in MRI-CGCM3 that was used for CMIP5 simulations, particularly over the Southern Ocean, is significantly reduced in MRI-ESM2 that is used for CMIP6 simulations. Each modification that contributed to the reduction of the radiation bias was progressively reverted to the corresponding older treatment in order to examine their individual impacts on the ITCZ representation. Results show the double-ITCZ problem worsens almost monotonically when the excessive shortwave insolation over the Southern Ocean increases. The contribution of the atmosphere is about one third of the impact on the total northward energy transport and the corresponding response of the Hadley cell is related to the change in the double-ITCZ. However, our results also imply that the ITCZ bias cannot be completely resolved by the improvements of radiative flux alone and that there are other causes of the problem.

KEYWORDS
climate model, cloud, ITCZ, Southern Ocean

1 | INTRODUCTION

Most climate models have a positive bias in precipitation over the Southern Tropics, especially in a broad region off Peru. This common and longstanding bias is referred to as the double-intertropical convergence zone (ITCZ) problem and the cause has been discussed for many years (e.g., Bellucci et al., 2010; Mechoso et al., 1995; Oueslati & Bellon, 2015; Tian, 2015; Tian & Dong, 2020; Xiang et al., 2017). In the meanwhile, the excessive insolation of shortwave radiation over the Southern Ocean has been another common and longstanding issue in most climate models (e.g., Kawai & Shige, 2020; Lauer & Hamilton, 2013; Trenberth & Fasullo, 2010).

Kang et al. (2008, 2009) showed that the intertropical convergence zone (ITCZ) responds to heating in the extratropics using a slab-ocean model; the ITCZ shifts southward when the Southern Hemisphere extratropics are warmed. They explained the mechanism in terms of the energy budget. Hwang & Frierson (2013) found relationships between the shortwave radiation flux bias over the Southern Ocean and the double-ITCZ problem in multi-models from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor et al., 2012). However, Kay et al. (2016) and
Hawcroft et al. (2017) used atmosphere–ocean coupled models to show that the excess energy in the Southern Ocean is transported to the Northern Hemisphere more by the ocean than by the atmosphere. They suggested that the influence of radiation bias over the Southern Ocean on the ITCZ is much smaller than that predicted from slab-ocean experiments and theory. Some studies have tackled this topic using various experimental designs (e.g., Haywood et al., 2016; Hawcroft et al., 2018; Mechoso et al., 2016; Xiang et al., 2018) and an intercomparison project called the Extratropical–Tropical Interaction Model Intercomparison Project is ongoing in order to understand this issue on a multi-model basis (Kang et al., 2019; Kang, 2020).

The previous version of the MRI climate model, MRI-CGCM3 (Yukimoto et al., 2011, 2012), which was used for CMIP5 simulations, had a serious negative bias in the reflection of shortwave radiation due to an unrealistically small cloud radiative effect (CRE) over the Southern Ocean. The negative bias was reduced significantly in MRI-ESM2 (Kawai et al., 2019; Yukimoto et al., 2019), which is used in the CMIP6 (Eyring et al., 2016) simulations. The score of the spatial pattern of radiative fluxes for MRI-ESM2 is better than any of the 48 CMIP5 models (Kawai et al., 2019; Yukimoto et al., 2019). The double-ITCZ problem was very serious in MRI-CGCM3, but the southern ITCZ peak in precipitation is lowered and improved to some extent in MRI-ESM2 (Yukimoto et al., 2019). Tian & Dong (2020) also showed that the double-ITCZ bias is significantly reduced from MRI-CGCM3 to MRI-ESM2. According to the tropical precipitation asymmetry index (TPAI), MRI-CGCM3 is the worst model among the 25 CMIP5 models examined, while MRI-ESM2 is the eighth best model among the 26 CMIP6 models examined. However, the relationship between the improvement in radiation flux and that in ITCZ representation in the model was not investigated in detail.

The improvement in the radiation bias is achieved by the accumulation of modifications in various physical schemes related to clouds (Kawai et al., 2019). Therefore, we can intentionally increase the shortwave radiation bias over the Southern Ocean by turning the modifications back to the older treatments one by one. By doing this, we can quantitatively examine the relationship between shortwave radiation bias over the Southern Ocean and the ITCZ representation in MRI-ESM2. It is valuable to examine the relationship in the actual update of a climate model based on an Earth system model that can reproduce present climate realistically, since previous studies are based on sensitivity tests that purely examine the relationship under idealized forcings.

2 | DATA

2.1 | Model experiments

The control run (CNTL) uses the standard version of MRI-ESM2 and has the smallest shortwave radiation bias over the Southern Ocean. A new stratocumulus scheme (Kawai et al., 2017, 2019) that can better reproduce stratocumulus is used in MRI-ESM2. In the scheme, turbulence at the top of the boundary layer that can destroy cloud layers is suppressed when a stability index, the estimated cloud top entrainment index (ECTEI; Kawai et al., 2017), is larger than a threshold value. In the simulation EXP1, the new stratocumulus scheme is replaced by the old scheme (Kawai & Inoue, 2006). Additionally, in MRI-ESM2, the occurrence of shallow convection that can destroy stratocumulus clouds is prevented over the area where the conditions for stratocumulus occurrence are met; that is, ECTEI is larger than a threshold value. This has the effect of increasing marine stratocumulus. EXP2 is as EXP1, but the shallow convection conditional prevention is turned off. MRI-ESM2 also uses an improved Wegener–Bergeron–Findeisen process in the cloud microphysics. The improved process causes a higher ratio of supercooled liquid clouds, which increases optical thickness of the Southern Ocean clouds. EXP3 is as EXP2, but the treatment of the Wegener–Bergeron–Findeisen process reverts to the old one. In MRI-ESM2, the number concentration of cloud condensation nuclei originating from fine mode sea salt is doubled to take into account the marine aerosols in the Aitken mode that cannot be explicitly represented in the model. EXP4 is as EXP3 but with this doubling that results in an increase in the optical depth of marine low clouds turned off. See Kawai et al. (2019) for more details related to these processes.

These experiments are listed in Table 1 and the radiation bias is expected to monotonically increase from CNTL to EXP4. We ran the historical simulations with

| Stratocumulus scheme | CNTL | EXP1 | EXP2 | EXP3 | EXP4 |
|----------------------|------|------|------|------|------|
| Shallow convection conditional turning off | Yes | Yes | No | No | No |
| WBF effect | New | New | New | Old | Old |
| Fine sea aerosols | Yes | Yes | Yes | Yes | No |
these five settings using the atmosphere–ocean coupled model. The models were run from 1979 to 2014, and data for the 31 years from 1984 to 2014 were used for analysis to exclude the period of model spin-up.

2.2 | Observational data

Precipitation (1979–2013) from the Global Precipitation Climatology Project (GPCP; Huffman et al., 2009) and radiative flux (2001–2010) from the Clouds and Earth’s Radiant Energy Systems (CERES) Energy Balanced and Filled (EBAF; Loeb et al., 2009) product are used as observational climatologies. The atmospheric model intercomparison project (AMIP) sea surface temperature (SST) data (Taylor et al., 2000) are used as the SST observational climatology. Observation-based estimates of ocean and atmospheric heat transport are from Fasullo and Trenberth (2008).

3 | BASIC FEATURES OF MODEL EXPERIMENTS

Figure 1 shows the basic features of the five simulations over the Southern Ocean (30°–70°S). When the stratocumulus scheme is replaced by the old scheme (EXP1), low cloud cover decreases from 62 to 50% over the Southern Ocean (Figure 1(a)). In addition, low cloud cover decreases by about a further 3%, if shallow convection is permitted to occur even over the area of stratocumulus occurrence (EXP2 in Figure 1(a)).

When the new treatment of the Wegener–Bergeron–Findeisen process is replaced by the old treatment (EXP3), the ratio of liquid water path to the total water path (the sum of liquid and ice water path) decreases over the Southern Ocean from 86 to 79% (Figure 1(b)) due to the decrease in the ratio of supercooled liquid water. The change is clearer for higher latitudes and the ratio decreases from 82% to 70% in EXP3 over the region 60–70°S where supercooled liquid boundary layer clouds predominate (figure not shown). Figure S1 shows the liquid water path and ice water path for each experiment and it is clear that the ice water path increases and liquid water path decreases in EXP3. From EXP2 to EXP3, the increase in ice water path is 6 g m⁻² but the decrease in liquid water path is larger at 17 g m⁻². This is partly because (i) ice crystals can be converted to snow faster than liquid clouds are converted to rain and (ii) ice crystals fall in the sedimentation process in contrast to the calculation of no sedimentation for cloud droplets.

When the doubled number concentration of cloud condensation nuclei originating from fine mode sea salt is turned off (EXP4), column-integrated cloud droplet number concentration decreases (Figure 1(c)) without changes in liquid water path (Figure S1(a)) from EXP3 to EXP4.

All these cumulative modifications contribute to the decrease in the CRE, especially over the Southern Ocean. Figure S2 shows biases of upward shortwave radiative flux (W m⁻²) at the top of the atmosphere with respect to CERES-EBAF. The reflection of solar radiation is progressively further underestimated from the CNTL to EXP4 experiments especially over the Southern Ocean as well as off the west coast of the continents, including off California and off Peru, though the bias is quite small in the CNTL run.

4 | RESULTS

4.1 | Radiation and precipitation

The shortwave radiation flux at the top of the atmosphere (TOA) over the Southern Ocean increases progressively (downward: positive) from CNTL to EXP4 experiments (Figure 2(a)). The net (shortwave + longwave) radiation flux at the TOA (Figure 2(b)) also increases progressively from CNTL to EXP4 experiments, although the impact on shortwave radiation is partly compensated by the impact on longwave radiation (Figure 2(a)).
In fact, the impact on longwave radiation is caused more by the SST increase than by weakening of the positive longwave CRE due to cloud decrease. Figure 3(a) shows differences of radiative flux at the TOA with respect to the CNTL experiment for each experiment, averaged over the Southern Ocean (0°–360°E, 30°–70°S). The impact on the shortwave component is mainly attributed to the impact on CRE (i.e., decrease in negative shortwave CRE). In contrast, for the longwave component, the contribution of clear sky radiative flux is much larger than the contribution of CRE. This means that the change in excess shortwave radiative flux is partly compensated by the outgoing longwave radiation due to increased temperature, and that this effect is greater than that of reduced positive longwave CRE due to decreased clouds. Figure 3(b) shows the ratio of longwave components to shortwave flux difference. The shortwave flux changes are compensated by longwave clear sky radiation by 40% and longwave CRE by 10%. This is basically the same in the last 11 years (2004–2014) of the simulations, in which the climate is closer to the equilibrium state, with a slight increase in the contribution from clear sky radiation (Figure S3).

Figure 2(c) shows the impact on zonal mean precipitation. From the CNTL to EXP4 experiments, the peak in precipitation in the Southern Tropics increases and moves away from the GPCP observations (Figure S4 plots the precipitation bias based on the GPCP observations). This means that the double-ITCZ problem deteriorates from the CNTL to EXP4 simulations (See Figure S5 for the precipitation maps).

4.2 Relationships between radiation and ITCZ

For the analysis, several indexes are calculated including the asymmetry of extratropical radiative flux and CRE (Hwang & Frierson, 2013), the tropical SST asymmetry (Hawcroft et al., 2018), the TPAI (Hwang & Frierson, 2013), and the Southern ITCZ Index (Bellucci et al., 2010). The asymmetry of extratropical radiative flux or CRE (W m⁻²) is calculated as the average over 20°N–90°N minus that over 20°S–90°S (positive: downward, Hwang & Frierson, 2013). The tropical SST asymmetry (K) is calculated as SST over 0°N–20°N minus that over 0°S–20°S (Hawcroft et al., 2018). The TPAI (dimensionless) is defined as the precipitation over 0°N–20°N minus that over 0°S–20°S normalized by the total tropical precipitation (20°S–20°N) (Hwang & Frierson, 2013). The Southern ITCZ Index (mm day⁻¹) is defined as the annual mean precipitation over the 20°S–0°S, 100°W–150°W window (Bellucci et al., 2010).

There are clear relationships between the asymmetry of extratropical net radiative flux or CRE and tropical precipitation asymmetry or the Southern ITCZ Index for the model experiments (Figure 4(a,b,d,e)). More extratropical radiative flux over the Southern Hemisphere than over the Northern Hemisphere corresponds to more tropical precipitation in the Southern Hemisphere than in the Northern Hemisphere (Figure 4(a,b)) or more precipitation over the Eastern Tropical Pacific in the Southern Hemisphere (Figure 4(d,e)). Although the net (shortwave + longwave) radiation is used for the plots, the relationships essentially depend on the contribution of the shortwave component (figure not shown).

Figure 4(c) shows that the relationship between the tropical SST asymmetry and the tropical precipitation asymmetry is even stronger than other relationships plotted in Figure 4. This result is consistent with previous studies that found the importance of tropical SST in the double-ITCZ problem (e.g., Hawcroft et al., 2018; Mechoso et al., 2016; Xiang et al., 2017, 2018). In our simulation, although the asymmetry of extratropical net radiative flux or CRE decreases monotonically from CNTL to EXP4, the tropical SST asymmetry does not decrease...
from EXP2 to EXP4. One reason is that CRE due to low clouds increases only over the high latitude ocean in EXP3 and EXP4, while low clouds also increase over the low latitude ocean in EXP1 and EXP2 (Figure S6 shows the relationships between the asymmetry of extratropical net radiative flux or CRE and the tropical SST asymmetry).

Figure 4(a,b,d,e) shows that the alleviation of the double-ITCZ problem in MRI-ESM2 compared to MRI-CGCM3 is partly attributable to the reduction of the Southern Ocean radiation bias. However, it is also shown that although the asymmetry of extratropical net radiative flux is closer to the observations in the CNTL simulation, the simulation still has a negative bias in tropical precipitation asymmetry and a positive bias in Southern ITCZ Index. This fact and Figure 4(c) imply that the ITCZ bias cannot be completely resolved by improvement of radiative flux alone but that there are other causes of the problem (that affect the tropical SST asymmetry), at least in our climate model. Deep and shallow convection schemes probably also contribute to the problem.

### 4.3 Energy transport

Figure 5 shows the impacts on energy transport relative to the CNTL simulation (Figure S7 plots the raw data of...
The impacts on the cross-equatorial northward energy transport by the atmosphere and the ocean are positive and the energy transport monotonically increases from CNTL to EXP4. The contribution of the atmospheric transport is almost one third of the impact on the total northward energy transport. The larger contribution of the ocean to the change in transport is consistent with some previous studies, for instance, Kay et al. (2016) and Hawcroft et al. (2017). Figure S7 shows that the energy transport closely matches the observations in CNTL and the difference grows from CNTL to EXP4, especially for the ocean energy transport. The underestimate of the southward ocean energy transport in the Southern Hemisphere in MRI-CGCM3 and the improvement in MRI-ESM2 (Yukimoto et al., 2019) can be attributed to the improvement in radiative flux asymmetry due to these model modifications based on these results.

Although the contribution of the ocean to the northward energy transport is larger than the contribution of the atmosphere, the relationship between the greater excess of radiative flux over the Southern Hemisphere and a more striking double-ITCZ problem is still clear in Figure 4. The response of the atmospheric energy transport is mainly attributable to a response of the Hadley cell. The increase in the northward atmospheric energy transport corresponds to an increase in the upward stream south of the equator and an increase in the northward cross-equatorial stream in the upper atmosphere (Figure S8). This response of the Hadley cell corresponds to higher precipitation peaks in the Southern Tropics (Figure 2(c)).

5 | SUMMARY

The radiation bias over the Southern Ocean in MRI-ESM2 that is used for CMIP6 simulations is significantly reduced from that in MRI-CGCM3 that was used for CMIP5 simulations. In the present study, the relationship between the improvement in the radiation bias over the Southern Ocean and the alleviation of the double-ITCZ problem in the actual update of our climate models was investigated. Each modification that contributed to the reduction in Southern Ocean radiation bias was progressively reverted to the corresponding old treatment that was used in MRI-CGCM3 to examine the effect on ITCZ representation.

The results show that the double-ITCZ problem worsens almost monotonically when the excessive shortwave insolation over the Southern Ocean increases due to decreased low cloud cover (EXP1 and EXP2), decreased ratio of supercooled liquid water (EXP3), and decreased cloud droplet number concentration (EXP4). The relationship was quite clear (Figure 4), as found by Hwang and Frierson (2013), even though the contribution of the ocean to the northward energy transport is larger than the contribution of the atmosphere (Figure 5) as previous studies using coupled models (e.g., Hawcroft et al., 2017; Kay et al., 2016) have shown. In addition, our results imply that the ITCZ problem is more directly affected by the tropical SST asymmetry (Figure 4), which is probably greatly influenced by the asymmetry of inter-hemispheric radiation flux (Figure S6). In our simulations, changes in shortwave radiation are compensated by increased outgoing longwave radiation due to SST increase by 40% and reduced positive longwave CRE by 10% (Figure 3). In addition, about one third of the total change in energy transport responding to the net radiation flux changes is contributed by the atmosphere (the rest is by the ocean) in our simulations (Figure 5).

In our model development process for CMIP6, we focused on the Southern Ocean shortwave radiation bias and the modifications mentioned in the present study were implemented to reduce the bias. It is interesting that
the double-ITCZ problem was alleviated simultaneously, although we did not try to reduce the tropical precipitation bias intentionally. However, our results (Figure 4) also imply that the ITCZ bias cannot be completely removed by the improvement of radiative flux alone because the double-ITCZ problem is still present even though the asymmetry of radiation flux is already a little larger than in the observations. There must be other causes of the longstanding double-ITCZ problem, at least in our climate model, and further studies are needed to solve the problem including the sensitivity to deep convection and shallow convection schemes.

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AUTHOR CONTRIBUTIONS

Hideaki Kawai: Conceptualization; formal analysis; investigation; writing - original draft. Tsuyoshi Koshiro: Investigation; writing-review & editing. Seiji Yukimoto: Formal analysis; writing-review & editing.

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