Dear Referee #1,

We would like to thank you for your constructive comments and suggestions to improve the quality of our manuscript "Mitigation of the double ITCZ syndrome in BCC-CSM2-MR through improving parameterizations of boundary-layer turbulence and shallow convection" by Yixiong Lu et al., submitted to *Geoscientific Model Development*.

We have revised our manuscript and answered all the comments given by the referee. Please find our detailed point-by-point responses to the comments below. The reviewer's comments are in black, and our responses are in red.

Best regards,

Yixiong Lu and all co-authors

Response to Anonymous Referee #1

Review of

Mitigation of the double ITCZ syndrome in BCC-CSM2-MR through improving parameterizations of boundary-layer turbulence and shallow convection
Yixiong Lu, Tongwen Wu, Yubin Li, & Ben Yang

General
The authors report the improvement in the known 'double ITCZ bias', common in most coupled climate models, in the BCC-CSM2-MR model. The authors aptly report the improvement caused by the implementation of new boundary layer and shallow cloud parameterisations. I am not an expert in the associated parameterizations, and so not in a position to critically assess the technical and physical aspects related to their implementation. I do have some comments with regards to the reported improvement in the double ITCZ bias and on the general presentation of the analysis. I find the work to be generally well presented and within the scope of GMD. With regards to the mitigation of the double ITCZ bias, I encourage the authors to take into consideration the comments provided below.

We would like to thank the reviewer for taking the time to carefully read our manuscript, for very valuable comments and suggestions and English grammatical corrections. We have revised our manuscript and answered all the comments given by the reviewer.

Specific comments

1. Adding the values of critical parameters used in the revised parameterization would help the readers and enable the reproducibility of the reported results (e.g., in Eq. 5).

Thank you for your suggestions. The parameter A in Eq. 5 is not a constant and the computation method has been added in the revised manuscript, as follows,

"Following Bretherton and Park (2009), A is expressed as

$$A = 0.1(1 + 30E), \tag{6}$$

where E is the evaporative enhancement, which is parameterized as

$$E = 0.8Lq_l^{ct} / \Delta s_{vl}. \tag{7}$$

L is the latent heat of vaporization, q_l^{ct} is the cloud-top liquid water content, and Δs_{vl} is the jump in the liquid virtual static energy across the cloud-top entrainment zone."

Please note that two more equations are included and the equations in the revised manuscript have been renumbered.

2. Line 27: the double ITCZ bias is seen year-round in the central and western Pacific, but only during the SH rainy season over the eastern Pacific (and Atlantic). (See Adam et al. 2018 and Li & Xie 2014)

   Thank you for the comment. The double ITCZ bias indeed has distinct seasonal and regional characteristics, which have been clarified in the revised manuscript as follows,

   "Specifically, the double ITCZ bias is primarily seen in the Pacific and Atlantic sectors, and during the southern hemisphere rainy season (Li and Xie, 2014; Adam et al., 2018)."

   These two cited papers have been added in the reference list.

3. Lines 228-230: increased cloud fraction in the subtropical eastern Pacific cools surface waters which subduct and eventually end up in the cold tongue. It is worth mentioning this coupling mechanism here, which was shown to have an important effect by Burls et al. (2017).

   Thank you for the comment. This coupling mechanism has been added in the revised manuscript, as follows,

   "As shown in Burls et al. (2017), increased cloud fraction in the subtropical eastern Pacific has an important effect on the cold tongue by cooling sea surface waters which subduct and eventually end up in the equatorial Pacific."

The cited paper has been added in the reference list.

4. Lines 255-256: both the surface temperature and surface temperature gradient have an important effect on boundary layer and deep convection, as shown by Back and Bretherton (2009). The effect of BL convergence by SST gradients is not accounted for in the analysis.

   Thank you for the comment. The boundary layer convergence is an important aspect of ITCZ. Thank you for reminding us to add this analysis. We added comparisons of surface convergence in Figure 10, replacing the wind stress magnitude. Discussions are included as follows,

   "Boundary layer convergence is primarily affected by SST gradients and can be usefully viewed as a forcing on deep convection over the tropical oceans (Back and Bretherton, 2009a, b). It is clearly shown in Figure 10 that NEW_cmip produces relative divergence in the southern Pacific between 5°S and 15°S compared to REF_cmip, which corresponds to the eliminated southern ITCZ rainfall band resulting from weaker deep convection."

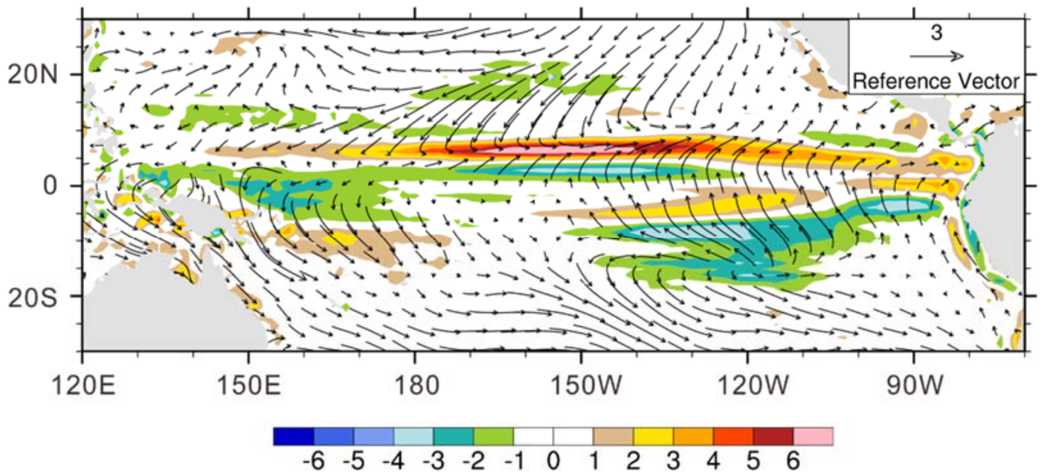

   Figure 10. The difference of annual mean wind stress vector and surface convergence (shaded, $\times 10^{-6}$ s^{-1}) between NEW_cmip and REF_cmip.

   The cited papers have been added in the reference list.

5. Lines 272-274: Indeed, the biases in the eastern Pacific and Atlantic are reduced. However, a negative bias in the Equatorial Indian Ocean seems to get worse. Are A the biases in the Indian Ocean, as well as the changes in the revised model, also related to the BL parameterization?

   Thank you for the comment. Indeed, the simulated precipitation in the equatorial Indian Ocean has decreased in the revised model. Precipitation simulation is a complex problem, involving many processes such as deep convection parameterization scheme and cloud microphysical parameterization scheme. The modification of boundary layer and shallow convection schemes in the model will affect the performance of deep convection and cloud microphysical schemes, and then cause changes in precipitation simulation. These discussions have been added in the revised manuscript, as follows,

"It should be noted that precipitation simulation is a complex problem, involving many processes such as deep convection and cloud microphysics. The modification of boundary layer and shallow convection schemes in the model will affect the performance of deep convection and cloud microphysical schemes, and then cause changes in precipitation simulation. For example, a negative bias in the equatorial Indian Ocean seems to get worse in NEW_cmip, which may be due to the indirect effects of changes in boundary layer and shallow convection parameterizations."

6. Fig. 4: The cold tongue bias seems to persist in the revised model. (This is mentioned lated in the analysis.) Since the cold tongue bias is known to be closely linked to the double ITCZ bias, it is interesting and worth highlighting that an improvement is achieved only in one aspect of the bias.

   Thank you for the comment. Accurate simulation of the ITCZ-cold tongue complex depends on multiple atmospheric and oceanic processes, and this study focuses on the role of parameterized boundary-layer turbulence and shallow convection. Discussions are added in the revised manuscript as follows,

   "It is interesting and worth highlighting that the cold tongue bias, which is closely linked to the double ITCZ bias, persists NEW_cmip, implying that other parameterized processes, e.g., deep convection and oceanic circulations, may play an important role in achieving more improvements."

7. Lines 286-293: Both the anti-symmetric and symmetric components of the precipitation bias are significant (e.g., Adam et al. 2016). I suspect that the equatorial precipitation index (Adam et al. 2016, 2018), which was found to be strongly correlated with other phenomena (Popp and Lutsko 2017), will be quite different from observations in the revised model, in particular since equatorial precipitation in Fig. 5 is lower than observed.

   Thank you for the comment. We considered your suggestion as to computing the equatorial precipitation index. You are right. The equatorial precipitation index is not improved in the revised model. The observed equatorial precipitation indices are 0.136 in GPCP and 0.110 in CMAP, respectively. The simulated indices are much smaller, which is 0.013 in the original model and further reduces to -0.008 in the revised model. The worse index is consistent with less equatorial precipitation in the revised model. We have included these discussions in the revised manuscript, as follows,

"On the other hand, the symmetric component of the tropical precipitation is quantified using the equatorial precipitation index E_p, defined as (Adam et al., 2016, 2018)

$$E_P = \frac{\overline{P}_{2^\circ S-2^\circ N}}{\overline{P}_{20^\circ S-20^\circ N}} - 1 . \quad (10)$$

In the case of double ITCZ that straddle the equator and when the equatorial precipitation vanishes, E_p assumes its minimum value $E_p = -1$. The more strongly peaked tropical precipitation is on the equator, the larger E_p. E_p is also found to be largely correlated with the difference in zonal mean precipitation between the absolute maximum and the equator (Popp and Lutsko, 2017). The observed equatorial precipitation indices are 0.136 in GPCP and 0.110 in CMAP, respectively, whereas the simulated values are much smaller, which is 0.013 in REF_cmip and further reduces to −0.008 in NEW_cmip. The worse index in NEW_cmip is consistent with less equatorial precipitation shown in Figure 5."

Please note that a new equation is added and the equations in the revised manuscript have been renumbered. Also, the cited papers have been included in the reference list.

8. Section 4.4 and Fig. 11: This is an odd Figure. According to classic theory, wouldn't it be the curl of the wind stress that affects the zonal ocean currents, rather than the intensity of the Walker circulation? In any case, Fig. 11 and the short treatment of this potentially important aspect seem perfunctory. I would suggest either omitting this section from the paper or providing a more detailed and complete analysis.

Thank you for your comments and suggestions. We have provided a more detailed and complete discussion about Figure 11. This figure is intended to illustrate the effects of enhanced southeasterly wind stress in and northwest of the Southeast Pacific region on the South Equatorial Current. We rewrote Section 4.4 as follows,

"Because of the strengthened southeasterly wind stress in and northwest of the SEP region, the south equatorial current in the upper ocean is enhanced. Figure 11 shows the longitude-depth cross section of zonal oceanic current and temperature averaged over 5°S – 10°S for the difference between NEW_cmip and REF_cmip. Compared with REF_cmip, the climatological westward zonal current in NEW_cmip over 5°S−10°S is enhanced by more than 8 cm/s above 120 m over the central to eastern Pacific. Further analysis indicates that the simulated subsurface temperature is reduced by more than 2 K above 80 m east of 135°W in NEW_cmip. Apparently, the enhanced westward ocean current over the whole zonal band helps transport cooler water from east to west and prevents the warm water in the western Pacific from extending eastward in NEW_cmip."

9. 5.2 Indeed the HR model seems to dramatically improve the representation of tropical precipitation. However the reader is left curious and confused. The authors claim that it is the UWMT that accounts fo the major improvement in the HR model but provide virtually no support for this claim.

   Thank you for the comment. To support the claim that the major improvement in the HR model benefits from the UWMT boundary-layer turbulence and modified Hack shallow convection schemes, we have added a subplot in Figure 13 showing the precipitation simulation result from BCC-CSM2-HR with old boundary layer and shallow convection schemes. Correspondingly, we adjusted the sentences in the second paragraph of section 5.2, as follows,

   "During the transition from BCC-CSM2-MR to BCC-CSM2-HR, the atmospheric component increased its horizontal resolution from T106 (~ 1.125°) to T266 (~ 0.45°) with a higher model top, and the physics package was essentially updated, especially the deep convection scheme. Furthermore, the oceanic component was upgraded to the Modular Ocean Model version 5 (MOM5). However, previous versions of BCC-CSM2-HR suffered from the double ITCZ syndrome until the UWMT and modified Hack schemes were introduced. Before improving parameterizations of boundary-layer turbulence and shallow convection, BCC-CSM2-HR simulated a southern rainfall band with excessive eastward extension over the central and eastern Pacific and two nearly parallel rain belts over the equatorial Atlantic (Figure 13a). This suggests that the boundary-layer and shallow convection schemes contribute primarily to the double ITCZ bias in BCC-CSM2-HR. The tropical precipitation patterns simulated in the frozen version of BCC-CSM2-HR, which is equipped with new boundary-layer turbulence and shallow convection schemes, barely manifest a double ITCZ, as shown in Figure 13b. The triangular-shaded dry region in the SEP reproduced by BCC-CSM2-HR resembles the observed much better than that simulated in the revised BCC-CSM2-MR, probably due to the improved interactions among the boundary-layer turbulence, shallow convection, and other processes. Anyway, improving parameterizations of boundary-layer turbulence and shallow convection shows robustness in mitigating the double ITCZ syndrome in different BCC coupled models."

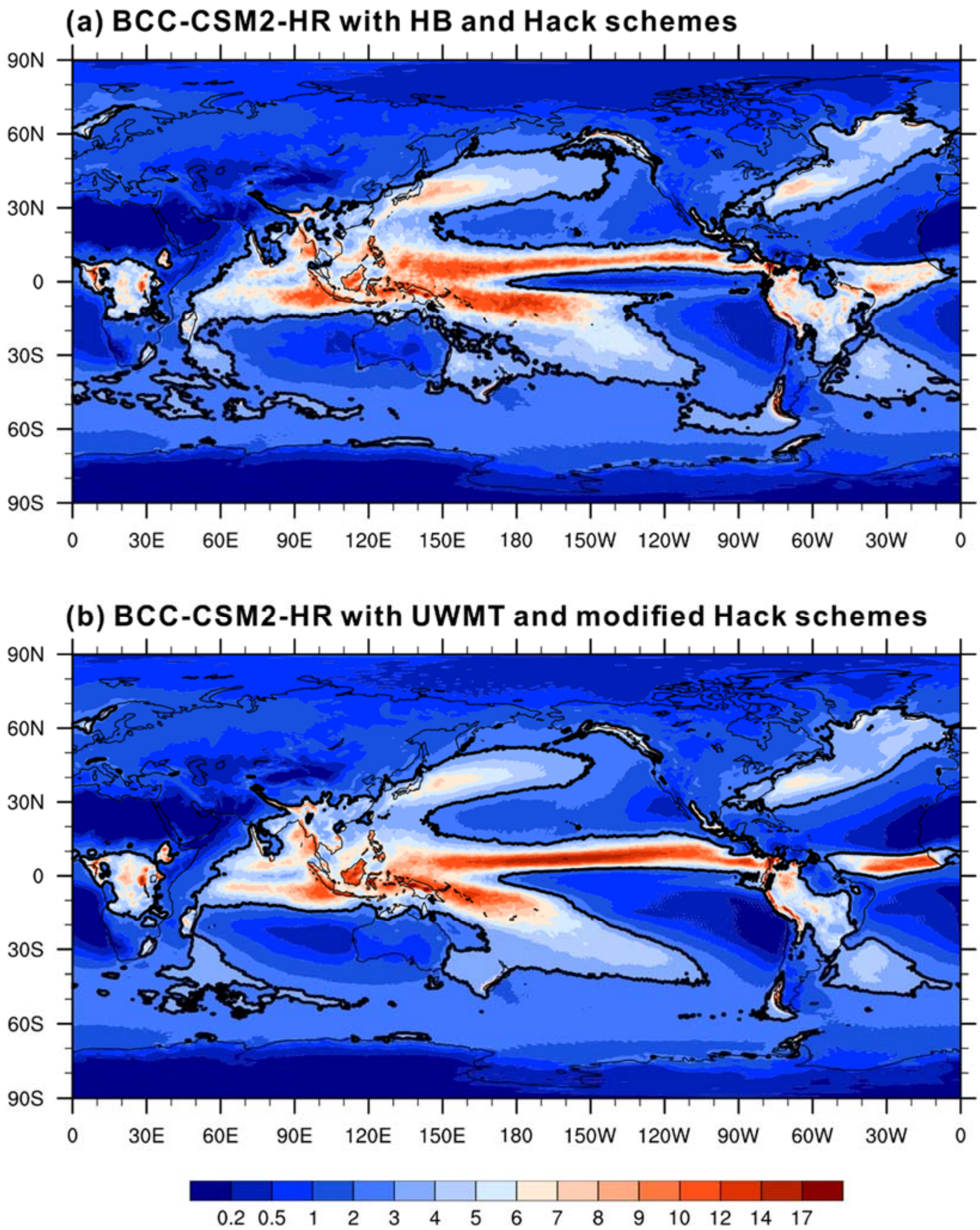

Figure 13. Annual mean precipitation rate (mm day^{-1}) from (a) intermediate version of BCC-CSM2-HR with original boundary-layer turbulence and shallow convection schemes, and (b) frozen version of BCC-CSM2-HR with new boundary-layer turbulence and shallow convection schemes. The 3 mm day^{-1} contour is included in bold for reference.

10. Lines 410-411: is this true also for the HR model?

Thank you for the question. In the high-resolution BCC-CSM2-HR, the cold tongue simulation seems to be unaffected by alleviating the double ITCZ bias, which may benefit from the improved deep convection parameterization. These discussions have been included in the revised manuscript.

Technical/editorial comments

14 promotes —> ameliorates

Done. We have changed 'promotes' to 'ameliorates'.

32 fake —> spurious

Done. Thank you for the correction.

37 impediment to what?

The sentence has been clarified as '… and it remains a serious impediment to model development'.

49 convection and cloud radiative effects

Done. 'convections and cloud' has been changed to 'convection and cloud radiative effects'. Thank you for the correction.

62 Previous attempts

Done. We have changed 'Previous studies' to 'Previous attempts'.

76 accounts for —> alleviates

Done. 'accounts for' is changed to 'alleviates'.

References

- Burls, N.J., Muir, L., Vincent, E.M. et al., 2017: Extra-tropical origin of equatorial Pacific cold bias in climate models with links to cloud albedo. Clim Dyn 49, 2093–2113
- Back, L.E. and C.S. Bretherton, 2009: A Simple Model of Climatological Rainfall and Vertical Motion Patterns over the Tropical Oceans. J. Climate, 22, 6477–6497
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- Li, G. and Xie S.-P., 2014: Tropical biases in CMIP5 multimodel ensemble: The

excessive equatorial Pacific cold tongue and double ITCZ problems. J. Climate, 27, 1765-1780

Thank you for providing these references which extend the breadth and depth of the manuscript. We have cited all the references.