Reply to Reviewer #1

Thank you very much for your careful review, detailed comments and constructive suggestions, which have helped greatly to improve the quality of our paper. The following is our point-by-point reply to your comments.

Comments:

In this study, the authors present the simulation of TCs in the FGOALS-f3 climate model. They use simulations at two different spatial resolutions to understand the impact of model resolution on TC simulation. I find the presentation not very good and highly disorganized. Also, the explanations provided are very rushed and hand-wavy. There's an over-emphasis on the role of MJO in TCs without first considering the basic large-scale environmental parameters governing TC formation and development first.

1. **Line 25:** Not sure what you mean by 'seasonal cycle of number of tropical cyclones increased by 50%'.

   Thank you for your careful correction. We have modified the statement from "seasonal cycle of number of tropical cyclones increased by 50%" to "Although the number of tropical cyclones increased by about 50% at the higher resolution and better matched the observed values in the peak month, both FGOALS-f3-L and FGOALS-f3-H appear to replicate the timing of the seasonal cycle of tropical cyclones." at lines 27–28.

2. **Line 55:** Replace 'following half-century' with 'last few decades'

   Thank you for your suggestion. We have replaced the statement from "following half-century" to "last few decades" at line 55.

3. **Line 60:** Cite past studies that have used high-resolution coupled GCMs to simulate TCs (Kim et al., 2014; Small et al., 2014; Li and Sriver 2018; Scoccimarro et al., 2017; Balaguru et al., 2020).

We are pleased to cite (at line 60-61) the following studies that have used high-resolution coupled GCMs to simulate tropical cyclones.

References:

Kim, Hyeong-Seog, et al. "Tropical cyclone simulation and response to CO_2 doubling in the GFDL CM2. 5 high-resolution coupled climate model." Journal of Climate 27.21 (2014): 8034-8054.

Small, R. Justin, et al. "A new synoptic scale resolving global climate simulation using the Community Earth System Model." Journal of Advances in Modeling Earth Systems 6.4 (2014): 1065-1094.

Li, Hui, and Ryan L. Sriver. "Tropical cyclone activity in the high-resolution community earth system model and the impact of ocean coupling." Journal of Advances in Modeling Earth Systems 10.1 (2018): 165-186.

Scoccimarro, E., et al. "Tropical cyclone interaction with the ocean: The role of high-frequency (subdaily) coupled processes." Journal of Climate 30.1 (2017): 145-162.

Balaguru, Karthik, et al. "Pronounced impact of salinity on rapidly intensifying tropical cyclones." Bulletin of the American Meteorological Society 101.9 (2020): E1497-E1511.

4. **Line 80:** Replace ‘controversial’ with ‘ambiguous’

   Thank you for your suggestion. We have replaced ‘controversial’ with ‘ambiguous’ at line 87.

5. **Lines 67-87:** This part could be better written and organized.

   Thank you for your suggestion. We have rewritten lines 68–92 as: “The increase in the horizontal resolution of GCMs has led to significant changes in the simulation of the variability of tropical cyclones. The changes can be broadly attributed to two reasons: (1) changes in the large-scale factors; and (2) the development of physical process parameterization and air–sea coupling related to the simulation of tropical cyclones. High-resolution GCMs need to not only give a better description of the structure of tropical cyclones, but should also simulate well the relationship between tropical cyclones and large-scale variabilities—for example, the El Niño–Southern Oscillation (ENSO), the Madden–Julian oscillation, wind shear and vorticity, and humidity—which is crucial in reducing the uncertainties in the simulation and prediction of tropical cyclones (Manganello et al., 2012, 2016; Zhang et al., 2016; Delworth et al., 2020). Previous studies have shown that there are significant changes in the ENSO as the horizontal resolution of GCMs increases (Philander et al., 1992; Kuntson et al., 1997; Schneider et al., 2003; Masson et al., 2012; Larson et al., 2013; Meehl et al., 2020) and the simulation results are mostly positive. However, these improvements in predicting the ENSO with an increase in horizontal resolution did not lead to improvements in the relationship between the ENSO and tropical cyclones (Matsuura et al., 1999; Bell et al., 2014; Krishnamurthy et al., 2016). There is also a relationship between the Madden–Julian oscillation and tropical cyclones (Liebmann et al., 1994; Hall et al., 2001; Camargo et al., 2008, 2009; Zhang et al., 2013; Klotzbach et al., 2014).

As the horizontal resolution in the models increases, some key parameters in the physical parameterizations are tuned to give a better performance (Bacmeister et al., 2013; Roberts et al., 2020)—for example, Lim et al. (2015) found that an increase in the threshold of minimum entrainment led to increasing tropical cyclone activity and Murakami et al. (2012) found that the constrained convective heating in the convective scheme induced intense grid-scale upward motion and promoted large-scale condensation, which favored the development of a more intense tropical cyclone. These artificial tuning methods might introduce more uncertainties in terms of the effects of resolution, giving rise to conclusions that are ambiguous to the tropical cyclone research community. In addition, considering the air–sea coupling process will also affect the simulation performance of tropical cyclone activities, especially with respect to the intensity. Scoccimarro et al. (2017) found that an increased horizontal resolution of the model components was not sufficient to simulate intense and fast-moving tropical cyclone events and that air–sea coupling with a higher coupling frequency helps to improve the performance of simulations of tropical cyclone intensity”.

6. **Lines 110-120:** While the atmospheric component is described in detail, there is only a one-line statement about the other components, especially the ocean model. Since this is a coupled simulation, and TC development is a highly coupled phenomenon, the authors must provide details of the ocean model as well.

   Thank you for your suggestion. The ocean model is an important component of GCMs. As suggested, we have added an introduction to the ocean model used in FGOALS-f3 at lines 124–126: “The oceanic component is the LASG/IAP Climate System Ocean Model Version 3 (LICOM3) (Liu et al., 2012). Orthogonal curvilinear coordinates and a tripolar grid are used in LICOM3 and the horizontal resolution can vary flexibly between 1o and 1/20o. A new advection scheme has also been updated in LICOM3 (Yu et al., 2018)”.

   Reference:

   Yu, Y., Tang, S., Liu, H., Lin, P., and Li, X.: Development and evaluation of the dynamic framework of an ocean general circulation model with arbitrary orthogonal curvilinear coordinate, Chinese Journal of Atmospheric Sciences, 42, 877–889, https://doi.org/10.3878/j.issn.1006-9895.1805.17284, 2018.

7. **Lines 180-185:** Is this due to positive SST biases in higher latitudes? It could also be the effect of steering flow being too strong in the North Atlantic and Northwest Pacific, which prevent TCs from making landfall.

Thank you for your suggestion. Because we only planned to include Tier 1 and Tier 2 of HighResMIP, which use a high-resolution SST, to force the atmospheric model, we carried out an AMIP-like run. As a result, the SST biases may not be considered in our results. The biases in the large-scale factors (e.g., the strong steering flow) related to the tropical cyclones in GCMs may contribute to the simulated biases in tropical cyclone activity in the WP and NA. So, as suggested, we have modified the sentence at lines 196–199 to: "This phenomenon also exists in the high-resolution GCMs that participated in the European Union Horizon 2020 project PRIMAVERA (Roberts et al., 2020). The biases in the large-scale factors (e.g., strong steering flow) related to the tropical cyclones in GCMs may lead to the simulated biases of tropical cyclone activities in the western Pacific and northern Atlantic oceans".

References:

Haarsma, R., Acosta, M., Bakhshi, R., et al.: HighResMIP versions of EC-Earth: EC-Earth3P and EC-Earth3P-HR–description, model computational performance and basic validation, Geosci. Model Dev., 13, 3507-3527, https://doi.org/10.5194/gmd-13-3507-2020, 2020.

Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vanniere, B., Mecking, J., Haarsma, R., Bellucci, A., and Scoccimarro, E.: Impact of Model Resolution on Tropical Cyclone Simulation Using the HighResMIP–PRIMAVERA Multimodel Ensemble, J. Climate, 33, 2557-2583, https://doi.org/10.1175/JCLI-D-19-0639.1, 2020.

Roberts, C. D., Senan, R., Molteni, F., Boussetta, S., Mayer, M., and Keeley, S.: Climate model configurations of the ECMWF integrated forecast system (ECMWF-IFS cycle 43r1) for HighResMIP, Geosci. Model Dev., 11, 3681–3712, https://doi.org/10.5194/gmd-11-3681-2018, 2018.

8. **Figure 4:** Why focus on only North Atlantic and Northwest Pacific in a GCM? To me, the improvement obtained going from a 100 km model to a 25 km model is

obvious and not very interesting. The authors can focus more on their results based on the high-resolution model and show global results instead of focusing on a couple of basins.

Thank you for your valuable suggestion. We agree with your view that it is not sufficient to show only the tropical cyclone intensities in the WP and NA. It is more interesting to show the intensities of tropical cyclones in each oceanic basin around the world. As suggested, we have modified Figure 4 to show the pressure–wind pairs in each ocean basin.

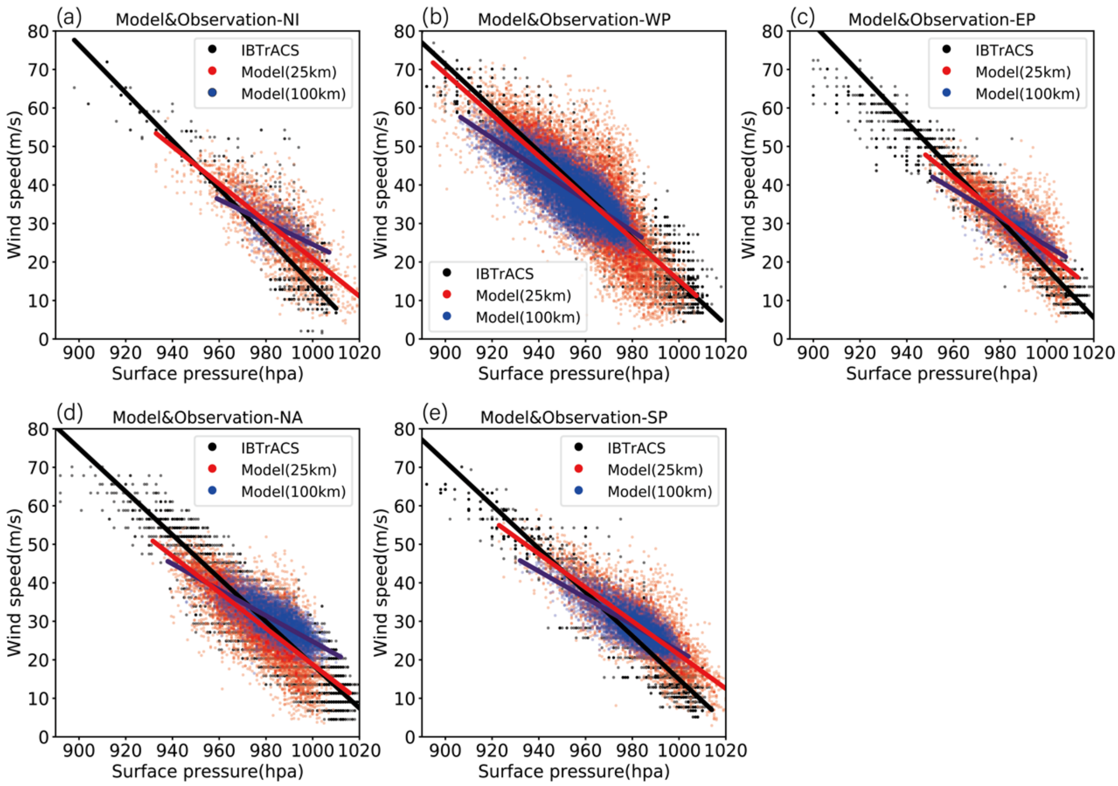

Figure 4. Pressure–wind pairs for each 6-hourly tropical cyclone measurement for FGOALS-f3-L (blue dots) and FGOALS-f3-H (red dots) and IBTrACS (black dots) in (a) northern Indian Ocean, (b) western Pacific, (c) eastern Pacific, (d) northern Atlantic and (e) southern Pacific. A linear regression (blue/red line for FGOALS-f3-L/H; black line for IBTrACS) is fitted to each distribution of pressure–wind pairs.

9. **Line 200:** The biggest increase in TC duration appears to be in the eastern Pacific. Why is this the case? Also, why is there an increase in TC lifetimes in general? Is it because of an increase in intensity? Or is it because of biases in steering flow?

   Thank you for your question. On one hand, the increased horizontal resolution in our convective precipitation scheme contributes to improvements in simulating the lifetime of tropical cyclones in general and the tropical cyclone counts and intensities are significantly increased. On the other hand, the biases in the large-scale factors (Figure 11) in FGOALS-f3-H are reduced (e.g., the wind shear), which contributes to the generation and development of tropical cyclones.

10. **Lines 210-220:** Why doesn't the seasonal cycle improve much in the eastern Pacific unlike every other basin?

    Thank you for your question. Few tropical cyclone counts have been identified in FGOALS-f3-L. When the horizontal resolution increased from 100 to 25 km, the negatives biases in the tropical cyclones in the EP and NA were improved. Both versions of the model retained the exact model physics and parameters and the only differences were the horizontal resolution and model time steps, which better met the rule of the HighResMIP. So, we think that FGOALS-f3-H at 25 km horizontal resolution is still not capable of capturing all the tropical cyclone activity in the EP and NA without tuning of the physical process parameterization. It is worth continuing to increase the horizontal resolution (C768; ~12.5 km). There are biases in the large-scale factors related to tropical cyclones in the EP and NA, which affected the generation and development of tropical cyclones.

11. **Figures 7 and 8:** If the simulation is free-running and not forced, I'm not sure what the point is in this comparison. In fact, I'd say this is meaningless. The only thing perhaps one can compare is standard-deviation or a measure of interannual variability.

Thank you for your question. According to the requirement of the HighResMIP, the experiment is running with an AMIP-like setting forced by the high-resolution SST.

Reference:

Haarsma, Reindert J., et al. "High resolution model intercomparison project (HighResMIP v1. 0) for CMIP6." Geoscientific Model Development 9.11 (2016): 4185-4208.

12. **Figure 9:** For observations, are you using the most intense TCs?

Thank you for your question. We used the most intense tropical cyclones for the observations to compare the simulated performance of the most intense tropical cyclone in FGOALS-f3.

13. **Section 4.1:** The jump from the previous section to this is rather sudden. I suggest presenting the analysis of the large-scale environment first before getting into MJO, ENSO etc. Note that these phenomena only modulate TC activity.

Thank you for your valuable advice. We agree with your view that the jump from the simulation performance of tropical cyclones to the MJO is rather sudden. The central aim of this paper is to introduce the CMIP6 version of FGOALS-f3 and its simulated performance of global tropical cyclone activity. The MJO is just one of the possible dynamical reasons we used to explain our results. As suggested, we have shortened the introduction of the relationship between the MJO and tropical cyclone activity because there are still some uncertain effects between them. As suggested, we now focus on the relationship between the ENSO and tropical cyclones. We have therefore modified Section 4.1 as:

4 Possible reasons for the simulated performance of tropical cyclones in FGOALS-f3

4.1 Modulation of tropical cyclone activity by the ENSO

There is a lot of evidence to suggest that the ENSO modulates the activity of tropical cyclones. Gray et al. (1984) found that tropical cyclone counts in the Atlantic Ocean are modulated by the ENSO. El Niño (La Niña) events enhanced (suppressed) westerly winds and led to stronger (weaker) vertical wind shear in the Atlantic basin, leading to an increase (decrease) in tropical cyclone counts. Camargo et al. (2004) found that the ACE in the western Pacific is positively correlated with ENSO indices. There are more intense and longer lived tropical cyclones in El Niño years than in La Niña years. Kim et al. (2011) found that the ENSO modulates tropical cyclone activity in the eastern Pacific Ocean. The track densities and genesis of tropical cyclones tend to be enhanced (suppressed) in eastern Pacific warming (cooling) years by strong (weak) westerly wind shear.

Figure 10 shows the average number of tropical cyclones and the ACE from El Niño, neutral and La Niña years. In the western Pacific basin (Figure 10a), there is no clear change in tropical cyclone counts compared with the variation of the ACE between El Niño and La Niña years. FGOALS-f3-H can capture these features in the observations; in particular, the simulation of the ACE is better than in FGOALS-f3-L. In the eastern Pacific basin (Figure 10b), FGOALS-f3 can capture the variation in tropical cyclone activities from El Niño to La Niña years, but the decreasing trend of tropical cyclone counts and the ACE in FGOALS-f3-L/H is weaker than in the observations. In the observations for the northern Atlantic basin (Figure 10c), there are more intense tropical cyclone events in La Niña years. FGOALS-f3 can reproduce the impact of the ENSO on tropical cyclone activity in the northern Atlantic Ocean and the simulated performance of tropical cyclones in FGOALS-f3-H is better than that in FGOALS-f3-L.

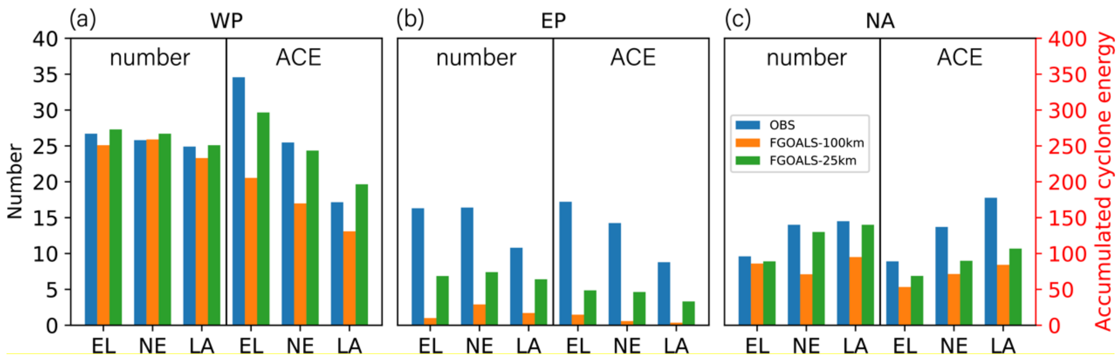

Figure 10. Bar chart showing the average number of tropical cyclones (left-hand panels) and ACE (right-hand panels) from El Niño (EL), neutral (NE) and La Niña (LA) years in the (a) western Pacific (WP), (b) eastern Pacific (EP) and (c) northern Atlantic (NA) oceans.

References:

Kim, Hye-Mi, Peter J. Webster, and Judith A. Curry. "Modulation of North Pacific tropical cyclone activity by three phases of ENSO." Journal of Climate 24.6 (2011): 1839-1849.

Camargo, Suzana J., and Adam H. Sobel. "Western North Pacific tropical cyclone intensity and ENSO." Journal of Climate 18.15 (2005): 2996-3006.

Gray, William M. "Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences." Monthly Weather Review 112.9 (1984): 1649-1668.

14. **Figures 10-13:** While figures 10 and 11 do show that the high-resolution model has a better representation of the MJO, its connection to TCs is very hand-wavy and not clear to me. Also, in both figures 12 and 13, MJO seems to have little effect on TCs in the Southern Hemisphere, which is strange. If the authors are really keen on understanding the impact of MJO simulation on TCs, they should perform an analysis something like that shown in this study: https://journals.ametsoc.org/view/journals/clim/27/6/jcli-d-13-00483.1.xml

    Thank you for your recommendation of this study, which discusses the impact of the MJO on tropical cyclone activities. We have read it and learned a lot. The main purpose of our paper is to introduce the FGOALS-f3 GCMs participating in

HighResMIP and to show the simulated performance of tropical cyclones in FGOALS-f3 at 100 and 25km horizontal resolution. As suggested, we have rewritten Section 4.1 to discuss the impact of the ENSO on tropical cyclone activity instead of the impact of the MJO.

Reference:

Klotzbach, P. J.: The Madden–Julian oscillation's impacts on worldwide tropical cyclone activity, J. Climate, 27, 2317-2330, https://doi.org/10.1175/JCLI-D-13-00483.1, 2014.

15. **Figure 14:** Expand the domain in the Atlantic all the way to the African coast and add panels for differences with observations. Although the GPI analysis is good, the way it is presented is not helping much. For instance, why is there a tendency in the model for a poleward shift in TCs? It's hard to see anything in the GPI analysis. What about SST biases?

Thank for your valuable advice. We quite agree with your view. We have shortened the relevant introduction of the GPI. As an alternative, we analyzed the large-scale factors associated with tropical cyclone activity (Figure 11). The improvement in the large-scale factors may contribute to the simulated performance of tropical cyclones in FGOALS-f3-H. We have also expanded the domain related to the NA to cover all of the basin.

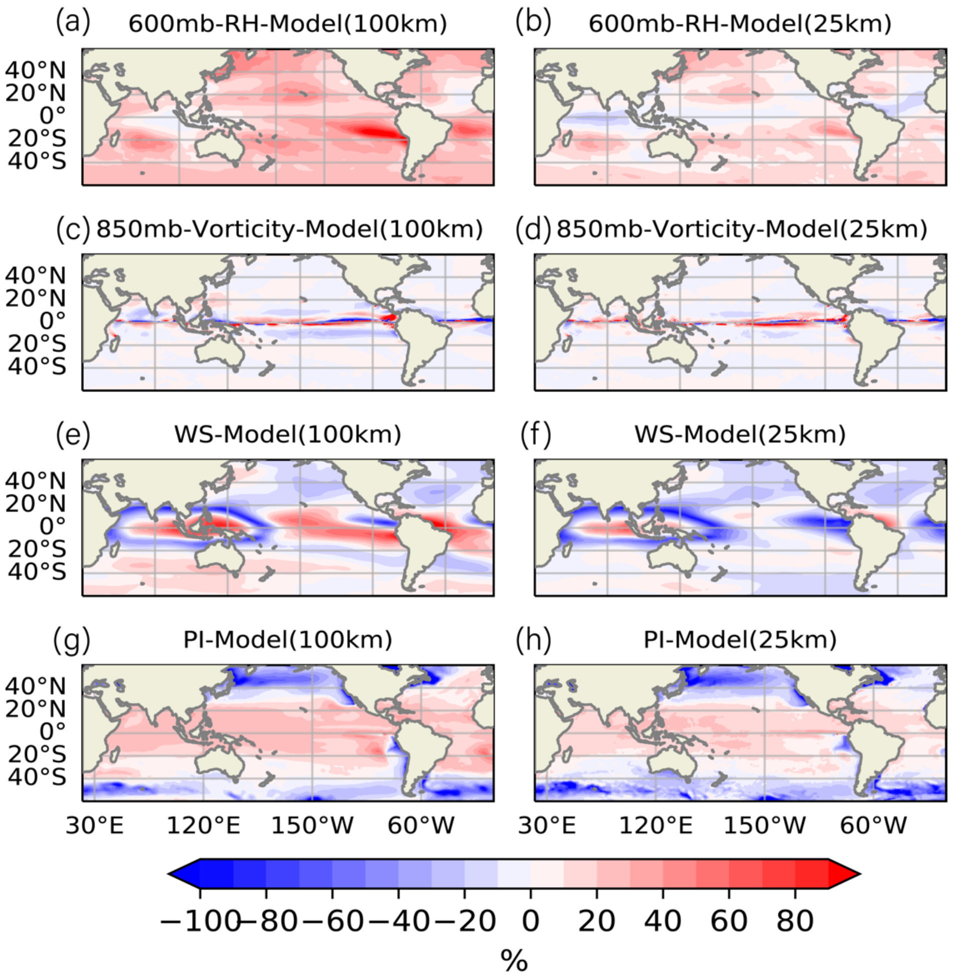

Figure 11. Biases in the large-scale environmental factors related to tropical cyclone activity between FGOALS-f3 and the observations. (a, b) Relative humidity biases at 600 hPa; (c, d) absolute vorticity biases at 850 hPa; (e, f) wind shear biases between 200 and 850 hPa; and (g, h) potential intensity biases.

16. **Figure 16 and 17:** Again, I don't understand the tendency of the authors to try and explain everything with MJO. There are other things besides it. For instance, what about African Easterly Waves in the Atlantic?

Thank you for your suggestion. The main purpose of this paper is to introduce the FGOALS-f3 GCMs participating in the HighResMIP and to show the simulated performance of tropical cyclones in FGOALS-f3 at 100 and 25 km horizontal resolution. The MJO is just one possible reason we use to explain the simulated performance. We agree with your view that the ENSO and other large-scale factors are important in modulating tropical cyclone activities in many basins. We therefore do not discuss the physical relationship between the MJO and tropical cyclones and have added an analysis of the ENSO (Figure 10) and large-scale factors (Figure 11). In the discussion section, we only give the results of the GPI pattern calculated using the multi-model mean (Figure 13).

17. **Tables 1-3:** There's no information presented in the paper on the length of simulations, etc.

Thank you for your correction. The length of the simulations is an important message and we have added it to Table 2.

Table 2. Comparison of resolutions, time steps and length of simulations in FGOALS-f3 for HighResMIP Tier 1.

Model configuration	100 km FGOALS-f3	25 km FGOALS-f3
Horizontal resolution	C96 (about 100 km)	C384 (about 25 km)
Number of vertical layers	32	32
Number of vertical remapping operations per physical time step with dynamical integration (k_split)	2	6
Number of small dynamic time steps between the vertical remapping operations (n_split)	6	15
Time step of dynamical core (min)	30	30
Time step of physical processes (min)	30	30
Frequency of radiative transmission (h)	1	1
Minimum time step of microphysics scheme (s)	150	150
Length of simulations	1950–2014	1950–2014