TerraMaris model evaluation paper: response to reviewers

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Response to Reviewer 2

We thank the reviewer for their positive comments on, and constructive criticism of, the manuscript. Their comments will help to improve the quality of the paper, particularly the discussion of air-sea coupling.

Replies to specific comments

1. The purpose of the simulations described in this paper is to provide a framework for investigating the important convective and convectively-coupled processes over the Maritime Continent, and how they are represented in models. It is well-known that important differences arise in the relationship between convection and SST on intraseasonal timescales between coupled and atmosphere-only simulations (see e.g. Figure 7 of Kim et al. (2010)). In atmosphere-only models on intraseasonal timescales convection tends to become in phase with SST as a result of the higher boundary layer moist static energy, whereas in coupled simulations the high SSTs are associated with periods of clear skies and low windstresses which lead to ocean warming. In the MJO this leads to an observed quadrature between convection and the SST in observations and coupled models compared to a more in phase relationship between convection and SST in atmosphere only models. We therefore do not intend to demonstrate that the mean-state and variability produced by the coupled runs are *better* than the same atmospheric model runs with prescribed SSTs when compared to observations; rather, we intend to demonstrate that coupled runs produce realistic mean-state and variability.

   We will re-word Section 5 on Air-Sea coupling to clarify this aspect.

   To demonstrate the robust qualitative difference in the phase relationship, we will add a second panel to Figure 13, showing the grid-point lead-lag relationship between precipitation and SST for the 2015-16 season atmosphere-only runs, compared to the same season for the coupled runs (see attached Figure 1). The correlations are weaker at all times in both MC2 and MC12 for the atmosphere-only run. Perhaps more importantly, the shape of the lead-lag relationship is different, with positive correlation at lead/lag 0, compared to approximately zero correlation in the coupled runs. This is in line with other studies in atmosphere-only models (with a fairly symmetric relationship about lag 0 since the SSTs cannot respond to the precipitation) and coupled runs (where higher SSTs promote the development of higher rainfall, but the precipitation and associated increased cloud cover then cool the SSTs). We note that in this configuration with both the boundary conditions and the prescribed SSTs coming from observations the relationship between SST and convection is perhaps more constrained to be close to the observed relationship than in a free running simulation, but even within that constraint the differences between the coupled and atmosphere-only simulations are large.

2. We agree that quantifying the overall domain-mean magnitude of the biases is useful. Therefore we will add a table of domain-averaged mean, mean bias, and RMSE (compared to the relevant reference dataset) for each variable considered in Figures 4-6, 9-11. For Figure 12, the mean and RMSE values shall instead be quoted in the accompanying text.

3. We agree that it is important to investigate the representation of clouds when considering convective processes, although cloud fraction itself is not necessarily the most relevant variable for understanding how the variability is represented in models. For example clouds may brighten leading to increases in reflected shortwave radiation or deepen leading to reductions in outgoing longwave radiation without any change in cloud fraction. Furthermore the definition of cloud fraction in models and observations can vary greatly between individual models (or reanalysis products) and depend strongly on the "observation" used to define them and so a direct comparison between models and observations is not always helpful. We have however compared both the outgoing longwave and reflected shortwave from both model simulations against observations (see attached Figures 2, 3) and find that in both MC2 and MC12 simulations the

biases are broadly consistent with typical GCM biases, and that the biases in MC2 tend to be reduced compared to MC12, suggesting a generally better representation of clouds in MC2 (consistent with a higher-resolution convection-permitting simulation). However, as with all other variables considered, the interannual variability is generally too high for both simulations (see attached Figures 4, 5). We will include a short discussion on these biases in the paper; the figures will be included as supplementary material.

We do not agree with the reviewer that biases in the 2m air temperature are particularly important for the kind of process studies for which we expect these simulations to be used. Moreover, over land, surface air-temperature will be particularly sensitive to orographic height and therefore not easy to compare even between the two models where the orography is different. We have therefore not considered this further.

4. We agree that the style of the paper is largely descriptive. We will add a few more explanatory/exploratory comments, but do not wish to present too much speculation without properly digging in to the causes of differences between the model runs, and between the model runs and observations. The purpose of creating this dataset is to explore precisely these questions of why higher resolution/explicit representation of convection changes e.g. the mean state and variability, including for instance coupling with equatorial waves and the MJO.

   In response to the reviewer's specific queries:

   - On the wet bias being stronger in MC2 than MC12: this was not unexpected, as it is fairly common in convection-permitting simulations (see response to Reviewer 1, Specific Comment 1).
   - On the SST biases being weaker in MC2 than MC12: this was unexpected, as the relaxation runs to determine the KPP flux corrections were only performed for the parametrized convection model at N1280 grid spacing. It would have been entirely reasonable to expect that the SST biases would therefore be worse in MC2.

     A full exploration of the mechanisms behind this difference is beyond the scope of this paper, but a preliminary analysis of the bias in both simulations suggests that the change in SST bias between MC2 and MC12 are broadly consistent with changes in the surface heat flux and these changes are also consistent with changes in the mixed-layer depth. This is especially clear around the islands of the Maritime Continent, with cooler SST and deeper mixed layers associated with lower heat fluxes into the ocean.

     However, the pattern of surface fluxes is complicated. The changes in surface radiation budget are broadly consistent with changes in the corresponding top-of-atmosphere fluxes, with some cancellation between the shortwave and longwave fluxes. The changes in the latent-heat (LH) flux are more complex, noting that the LH flux is defined as positive downwards and as such a positive change indicates decreased evaporation. The sign of the LH flux change is not consistent with it being driven directly by the SST, as the evaporation is generally higher in regions of colder SST. Similarly over large regions away from the islands evaporation is lower, but the surface wind stress is increased. The relative contributions of each component of the surface fluxes varies from region to region.

     To properly understand the differences in the SSTs would require a detailed analysis of the time evolution of the biases and would be regionally sensitive. It would be particularly interesting to look at these processes around the coastlines where it is clear there is a significant change in the representation of the diurnal cycle of convection, which is known to be associated with strong onshore/offshore circulations. This would make a good focus for a future study.

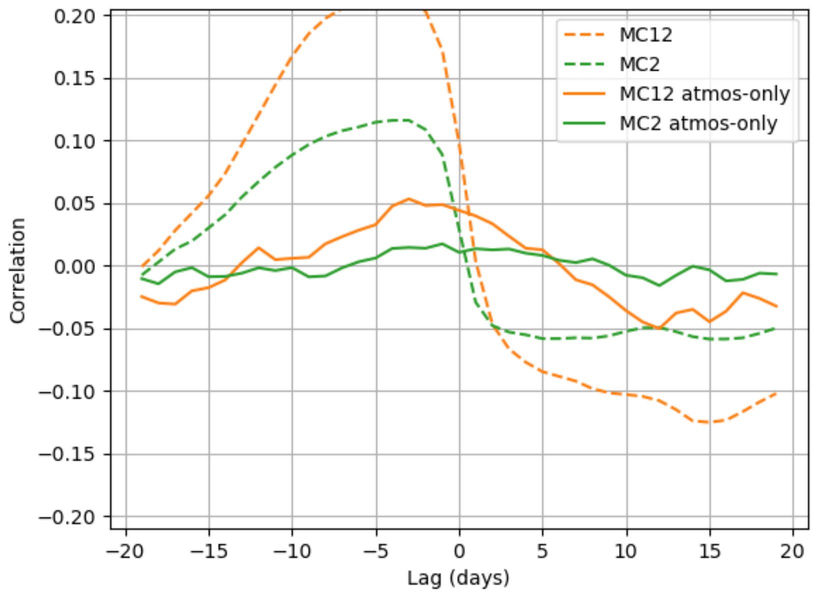

Figure 1: Grid-point Lead-lag relationship between precipitation and SST averaged across ocean grid-cells between 15° S and 3° N for the 2015-16 season, comparing the atmosphere-only and coupled model runs. For each dataset, the season was linearly detrended before computation to remove seasonal variability. Solid lines indicate atmosphere-only runs runs; dashed lines indicate coupled runs; MC2 is shown in green; and MC12 is shown in orange.

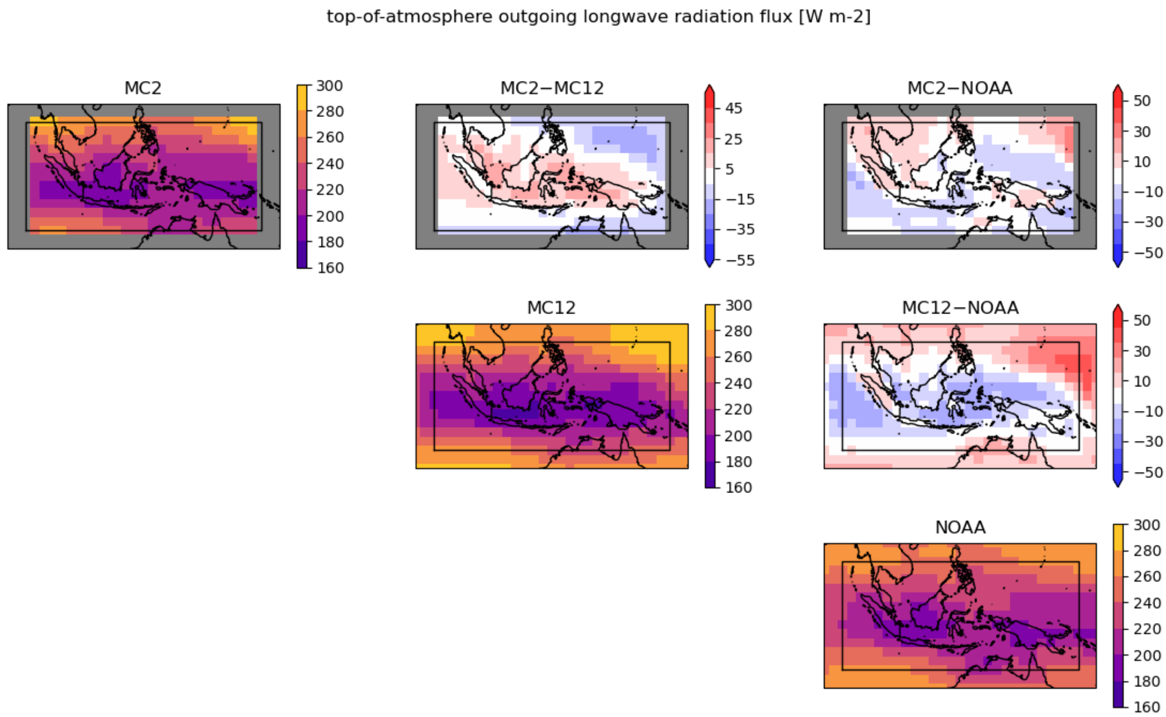

Figure 2: Mean outgoing longwave radiation and biases (W m^{-2}). Subplots along the diagonal indicate MC2, MC12, and NOAA daily OLR respectively. Upper off diagonal subplots show difference plots between each of the datasets.

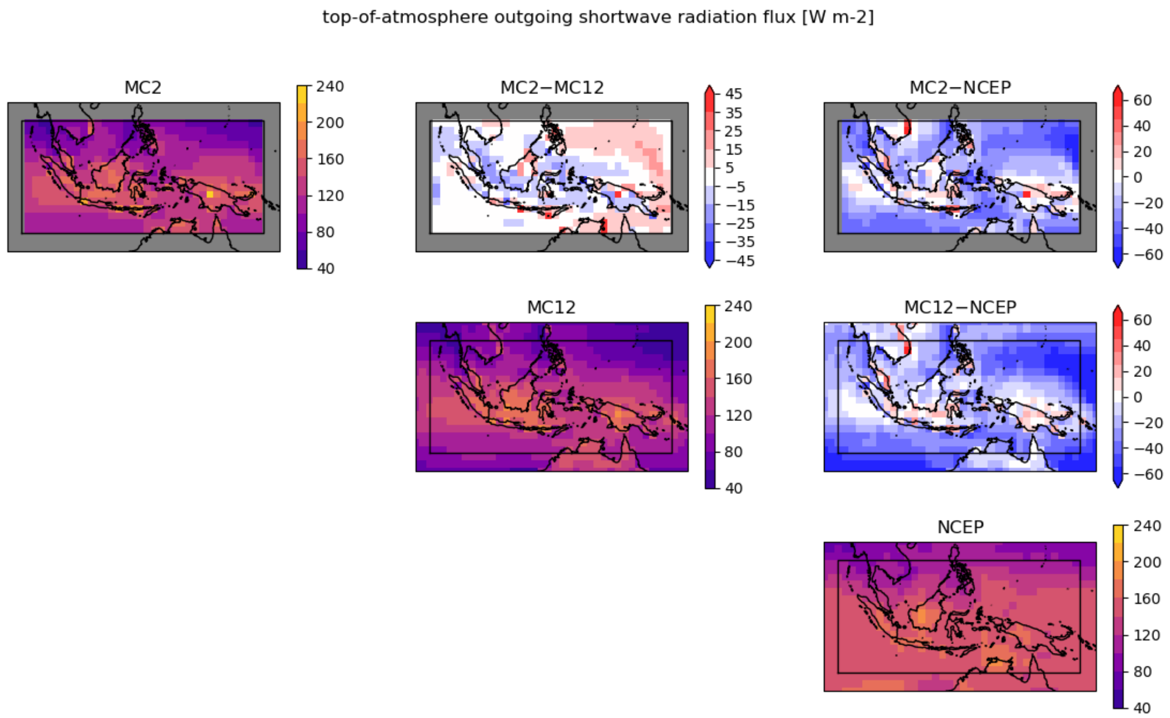

Figure 3: Mean outgoing shortwave radiation and biases (W m^{-2}). Subplots along the diagonal indicate MC2, MC12, and NCEP-NCAR reanalysis respectively. Upper off diagonal subplots show difference plots between each of the datasets.

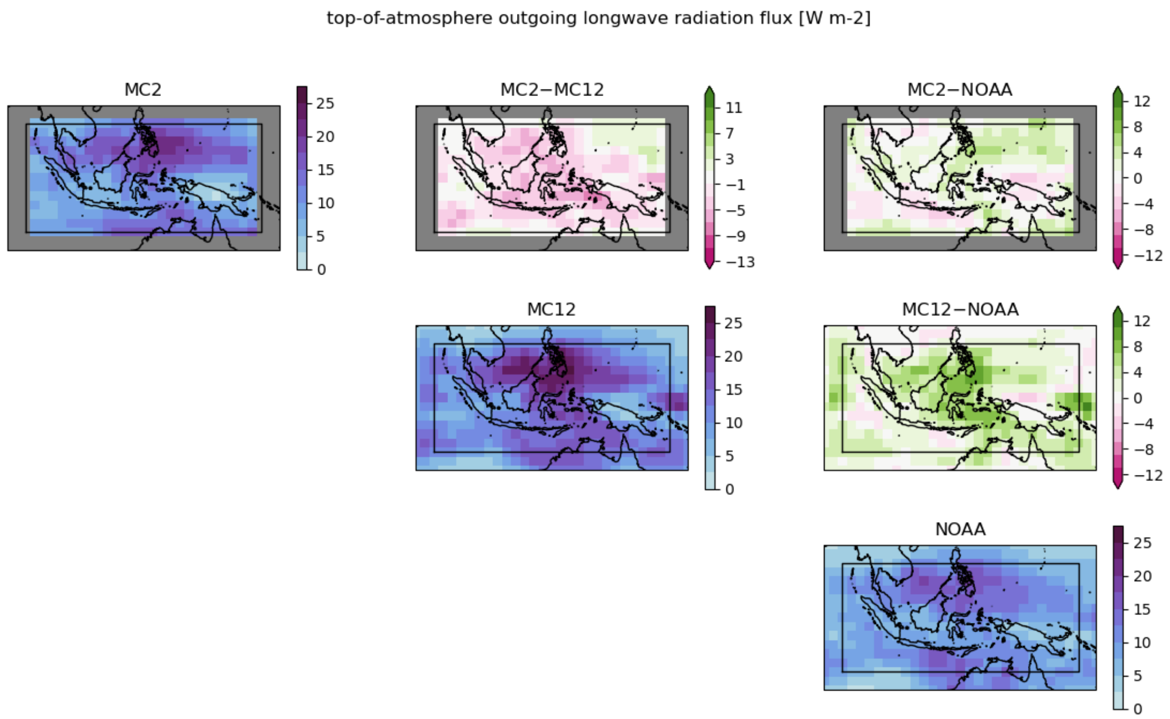

Figure 4: Interannual standard deviation of outgoing shortwave radiation and biases (W m^{-2}). Subplots along the diagonal indicate MC2, MC12, and NOAA daily OLR respectively. Upper off diagonal subplots show difference plots between each of the datasets.

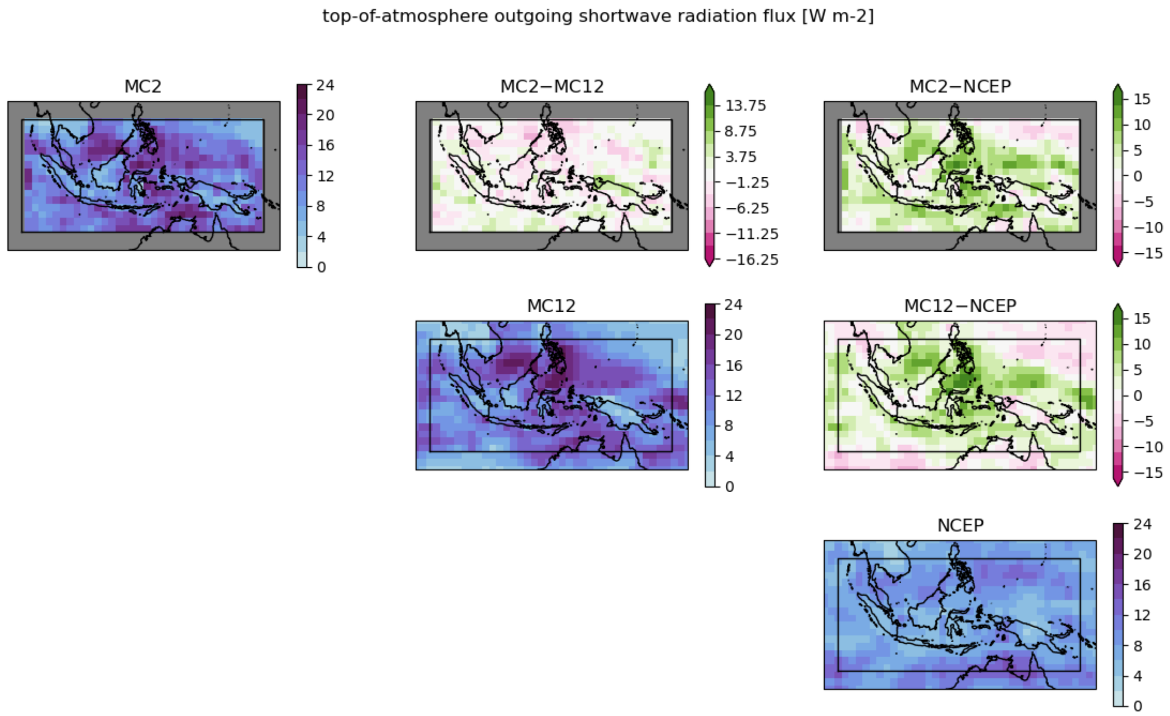

Figure 5: Interannual standard deviation of outgoing shortwave radiation and biases (W m^{-2}). Subplots along the diagonal indicate MC2, MC12, and NCEP-NCAR reanalysis respectively. Upper off diagonal subplots show difference plots between each of the datasets.

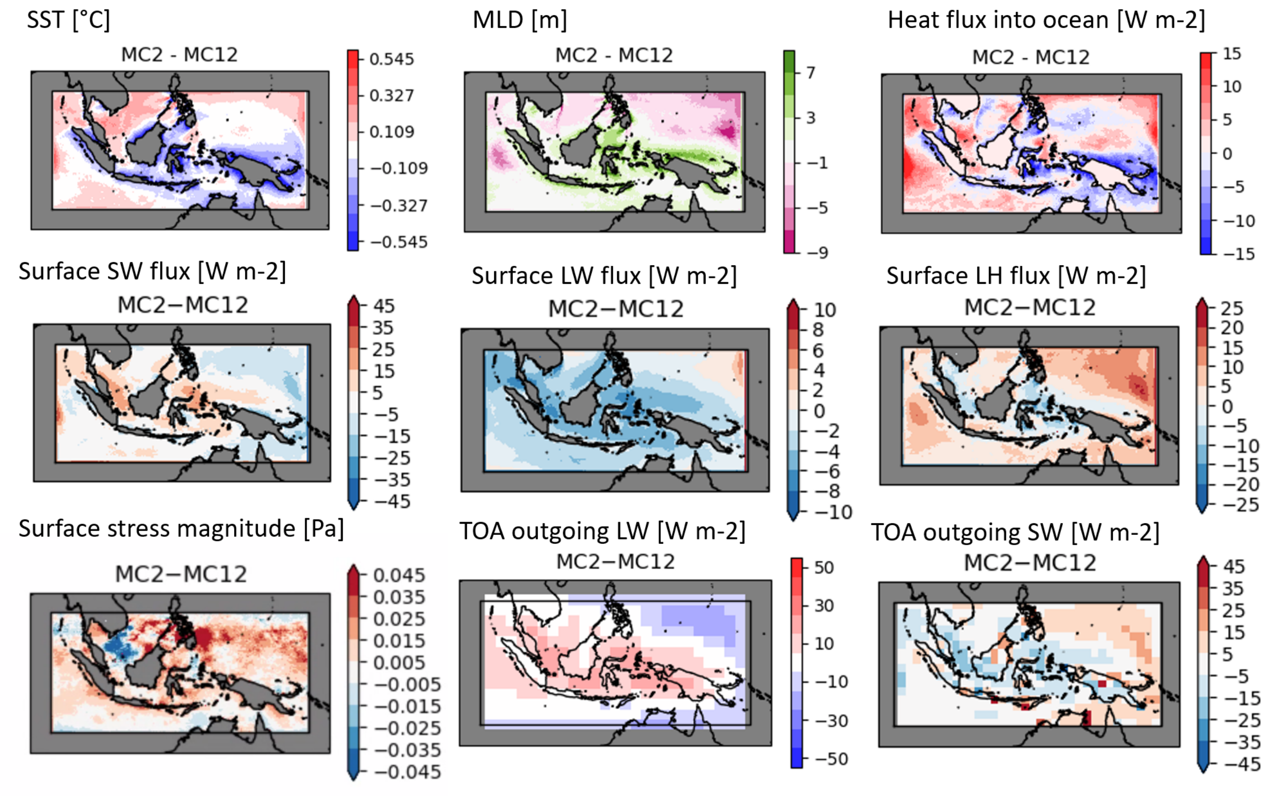

Figure 6: Spatial maps of differences between the all-season means of variables linked to the SST. Top row (L–R): sea surface temperature; mixed-layer depth; heat flux into the ocean. Middle row (L–R): downward surface shortwave flux; downward surface longwave flux; downward surface latent heat flux (a positive change corresponds to reduced evaporation). Bottom row (L–R): magnitude of downward surface wind stress; top-of-atmosphere outgoing longwave radiation flux (as an indication of cloud changes); top-of-atmosphere outgoing shortwave radiation flux (as an indication of cloud changes). Differences in downward surface sensible heat fluxes are not shown; their magnitude is less than ~ 3 W m^{-2} almost everywhere.

References

Kim, H. M., Webster, P. J., Hoyos, C. D., and Kang, I. S.: Ocean–atmosphere coupling and the boreal winter MJO, Climate Dyn., 35, 771–784, https://doi.org/10.1007/s00382-009-0612-x, 2010.